

## Architecture and evaluation of an automatic GNSS embankment deformation monitoring system

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### ABSTRACT

Road embankment deformation surveys are required to be undertaken periodically on hazardous areas to improve risk management, including loss of life and property. Deformation monitoring with global navigation satellite systems (GNSS) technology has been proved to be a very efficient and reliable method for measuring surface deformations. A fully automatic GNSS embankment deformation monitoring system (AGEDMS) has been designed and implemented for monitoring the stability of the surrounding area. The system was designed to automatically alert key project stakeholders when the movement exceeds a predefined threshold. The system consists of 5 GNSS monitoring stations and 2 base reference stations. Measurements from all 7 stations were recorded over about 3 weeks at a 15 second sampling rate. The system architecture and fundamentals are discussed, including data acquisition, transmission, processing, analysis and alarm configuration. In this study, both real-time solutions and post-processing methods are compared and investigated. A real movement detection example is presented which shows that the system can perform well to detect 5 mm movement in near real time for alerting purposes. As the multipath effects vary within different environments, a Survey Uncertainty (SU) method has been developed to provide an appropriate threshold limit for different cases.

**KEYWORDS:** GNSS, Road Embankment, Automatic Deformation Monitoring, Survey Uncertainty

## 1. INTRODUCTION

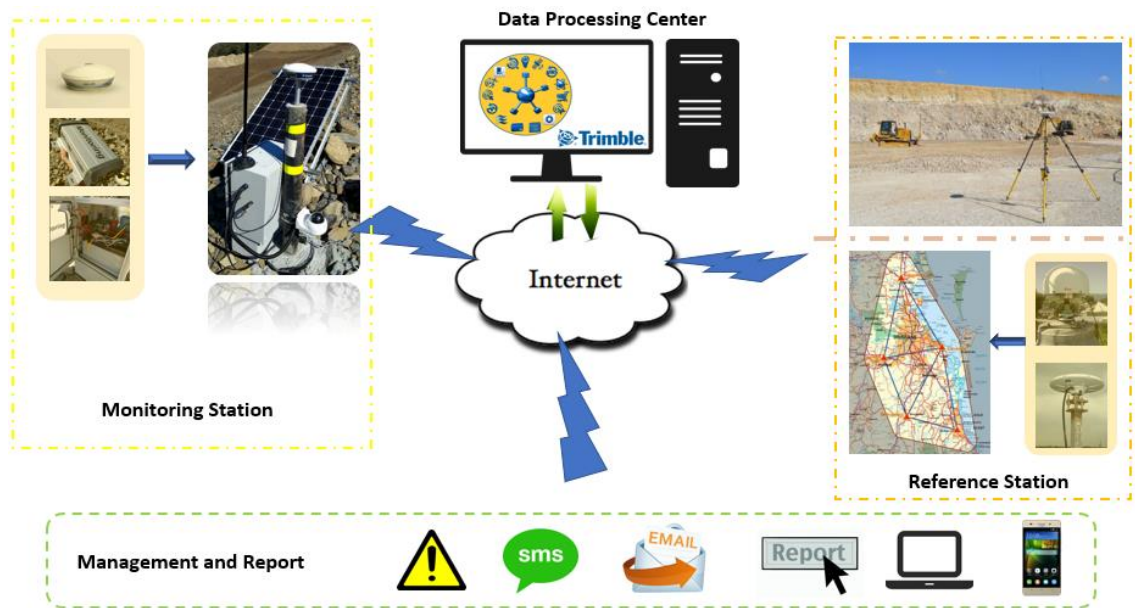
The monitoring of embankment deformation is a critically significant issue for minimising the risk of loss of life and damaging of property, infrastructure and environment, for example, when road embankments are constructed on soft foundations (Hsi and MacGregor, 1999). In Southeast Queensland, a trial embankment constructed with and without stone columns has been undertaken to assess the behaviour of soft clay when subject to embankment loading (Oh *et al*, 2007). It is a great challenge for engineers to realise a tight performance criterion in Post Construction Settlements (PCS) term (Xie and Kok, 2015).

Both geotechnical and geodetic monitoring techniques, particularly GNSS deformation monitoring applications, have been extensively studied to monitor and predict landslide motions or dam deformation to improve the risk management. A continuously operating GPS deformation monitoring system, so-called CODMS, has been developed that achieved  $\pm 2\text{mm}$  position accuracy (Hartinger and Brunner, 1999). In the largest earthfill dam project in America, a fully automatic Dam Deformation Monitoring (DDM) system has been developed, which uses GNSS measurements to provide geodetic information (Whitaker and Chrzanowski, 2000). The minimum norm quadratic unbiased estimation (MINQUE) method has been applied to calculate the GPS measurement accuracy in an embankment dam deformation analysis (Gökalp and Taşçı, 2009). A Continuously Operating Reference Station (CORS) network has been widely used in monitoring ground movement, deformation and subsidence due to its high reliability and cost-effective infrastructure. Zhang *et al* (2005) have investigated the feasibility using a regional CORS network data in deformation monitoring and analysed the precision and stability of the CORS network.

In this paper the authors present the design and architecture of an Automatic GNSS Embankment Deformation Monitoring System (AGEDMS). The results of a field example including the detailed data processing strategies and achievable accuracy are analysed and compared in terms of real-time data processing and post data processing situations. In addition, the performance of different data processing strategies for a real movement case study is discussed. In the last section, we conclude our study with the key findings and future suggestions.

## 2. SYSTEM ARCHITECTURE

To achieve the required accuracy at a reasonable cost, the developed AGEDMS comprises five types of components, including a data processing centre, reference stations, monitoring stations, user applications and a communication system. In an experiment described below, the user applications mainly involve data analysis/management and producing monitoring reports. The on-site field communications modules use GSM modems to send GNSS data to a data processing centre server which is a Trimble Pivot platform (Drummond 2010). Figure 1 shows the AGEDMS schematic diagram.



**Figure 1.** AGEDMS schematic diagram

## 2.1 Hardware

The characteristic features of the AGEDMS hardware are as follows.

- 1) Reference stations: Two base stations are used. One base station is a SPS855 GNSS Modular Receiver with a Zephyr 3 geodetic antenna. The other is a Trimble NetR9 with a Leica AT 504 GG Choke Ring antenna.
- 2) Monitoring stations: Five Trimble NetR9 Ti-M receivers with AG25 antennas.
- 3) Communications modules: Five data loggers convert the received GNSS data into TCP/IP format and send it back to the server with 4G modems.
- 4) Solar panels: Five solar panels and batteries lasting for 120 hours.
- 5) Observation pillars: Five concrete filled galvanised pipe observation pillars of 1m height.

Figure 2 shows the designed AGEDMS monitoring station. In general, access to the road embankment site is highly restricted due to the proximity of heavy plant in the area and the substantial risk of collapse or failure of the embankment. The equipment shown in Figure 2 can be installed within 1 hour per station by experienced staff.



**Figure 2.** An AGEDMS monitoring station

## **2.2 Software**

The Trimble 4D (T4D) Control software (Version 4.6.2) is installed on the data processing centre to provide multiple real-time GNSS processing engines for different monitoring tasks. It is the core of AGEDMS which controls the measurement, processes the data and provides scheduled reports or early warning messages.

In AGEDMS configuration, seven modules are applied in this application as follows (Trimble Navigation Limited 2016).

- 1) Device Manager: To configure and view the monitoring data from reference GNSS stations' receivers.
- 2) GNSS Receiver: To control the connected GNSS receiver data, analyse the consistency of multi-frequency data and detect the receiver errors.
- 3) Ephemeris Manager: To collect GNSS satellites orbit information and provide it to other modules.
- 4) Synchronizer: To collect and pass on data from Device Manager module and send it to the Processing Engines within the same epoch of data.
- 5) RTK Engine: To take the receiver observations and processes either baseline or station positions to determine and pass on high quality coordinates for a given set of stations within the monitoring network in real-time.
- 6) Post Processing Engine: To process stored raw GNSS receiver data and automatically estimate positions from baseline combinations with overlapping time sequences either in static mode or in kinematic mode.

## 7) Integrity Monitoring:

- a. To process position adjustment and update position over time;
- b. Data visualization and output position into the database;
- c. Alarm generation.

## 2.3 Observation Network Design

The purpose of the AGEDMS monitoring network is to mitigate risk and provide a continuity of monitoring throughout the life of the road embankment remedial works. The AGEDMS monitoring network should meet the following requirements (Kuang 1991; Blachowski et al, 2010):

- The distribution of monitoring stations must correspond to road embankment potential movement area;
- The reference stations have to be located outside the expected deformation area;
- Considering construction operation plans and budget limit;
- Physical constraints, e.g., the multipath influence and obstructions.

## 2.4 Alarms and Reports

The AGEDMS software platform can provide continuous data processing results in real-time and ‘on-time’ warnings of impending danger. The precision of the solutions need to satisfy sub-centimetre horizontal displacement detection requirements with 95% confidence. Depending on the severity and type of the alarms, the AGEDMS automatically sends SMS or e-mail messages to specific stakeholders, so users can log in at any time and determine the legitimacy or severity of the alarm. To avoid gross errors or false alarms occurring frequently, the alarm definition is configured as,

- More than two monitoring stations exceeding a trigger limit, or
- One monitoring station exceeding a trigger limit more than 30 minutes.

Table 1 lists the AGEDMS monitoring alarm and response action plan as follows,

Trigger	Trigger Level	Response action
NORMAL	Horizontal solution $\leq 5\text{mm}$ and Vertical solution $\leq 10\text{mm}$	<ul style="list-style-type: none"><li>• AGEDMS automatically sends scheduled normal report of previous monitoring results to all nominated stakeholders.</li></ul>
WARNING	Horizontal solution $> 5\text{mm}$ or Vertical solution $> 10\text{mm}$ either in one monitoring station lasting 30 minutes or occurring simultaneously in more than 2 monitoring stations	<ul style="list-style-type: none"><li>• AGEDMS sends email and SMS alert to all nominated stakeholders alerting of the type and magnitude of the monitoring results.</li><li>• AGEDMS continues monitoring and increase frequency of report.</li></ul>
ALARM	Horizontal solution $> 10\text{mm}$ or Vertical solution $> 20\text{mm}$ either in one monitoring station lasting 30 minutes or occurring simultaneously in more than 2 monitoring stations	<ul style="list-style-type: none"><li>• AGEDMS sends email and SMS alert to all nominated stakeholders alerting of the type and magnitude of notification.</li><li>• AGEDMS continues monitoring and increase frequency of report.</li><li>• Perform a visible inspection</li></ul>

**Table 1.** AGEDMS monitoring alarm and response action plan

As the response plan mentioned, a scheduled report including customised measurement plots/graphs/tables are sent to recipients. Figure 3 shows an example of daily monitoring report settings which help stakeholders to check the road embankment deformation information at the end of the workday.

Daily Monitoring Report (6 PM)

Report Schedule Settings		Schedule Details		Recipients
Name	Daily Monitoring Report (6 PM)	Next run date	N/A	
Report Type	Analysis Report	Last run date	6/08/2017 18:00:07	
Culture	English (AUS)	Status	Disabled	
Schedule period	Daily			
Time of day	18:00:00			

Analyses

Analysis Report Options

Include Series









No

Include Chart

Yes

Include Data

No

		Name	Analysis Type	Date Range Mode	Date Range	Owner	
<input checked="" type="checkbox"/>	1	Horizontal Displacement (Day Average)	Normal Chart	Rolling Window	Last 30 Days	System Administrator	 
<input checked="" type="checkbox"/>	2	Horizontal Displacement (Hour Average)	Normal Chart	Rolling Window	Last 14 Days	System Administrator	 
<input checked="" type="checkbox"/>	3	Vertical Displacement (Day Average)	Normal Chart	Rolling Window	Last 30 Days	System Administrator	 
<input checked="" type="checkbox"/>	4	Vertical Displacement (Hour Average)	Normal Chart	Rolling Window	Last 14 Days	System Administrator	 

Edit

Refresh

Preview

Run Now

**Figure 3.** AGEDMS report settings

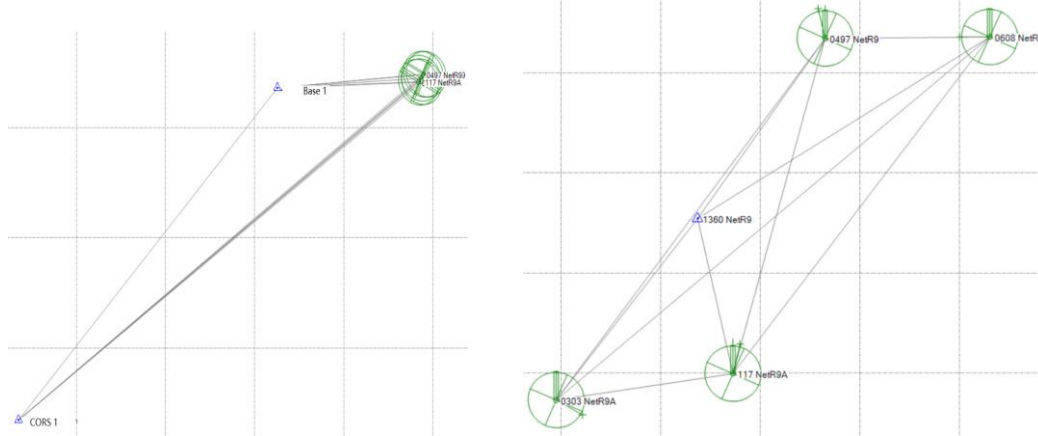
### 3. PRACTICAL EXAMPLE

An experiment road embankment about 100m length is selected in Queensland, which comprised of several hundred thousand cubic metres of fill on an existing slope. The AGEDMS was designed which included 2 reference stations and 5 monitoring stations. Additionally, one of the monitoring stations inside the deformation monitoring area served as an extra base station for internal quality check purposes with 50m baseline lengths.

Figure 4-1 shows the proximity of two reference stations which were applied in this experiment:

- Base 1: A construction base station (Tier 3) transferring data via TCP/IP client with a 4G modem, the distance to deformation monitoring area is about 1.5km.
- CORS 1: A Regulation 13 Certificated base station (Tier 2) through NTRIP broadcaster service, the distance to deformation monitoring area is about 4.8km.

Figure 4-2 shows the extra ‘base station’ situated approximately in the centre of deformation area.



**Figure 4-1.** Reference stations distribution

**Figure 4-2.** Monitoring stations distribution

### 3.1 Description of experiment processing strategy

The AGEDMS measurements were processed in two modes: real-time (RT) and post-process (PP) solutions. The real-time positioning result is used to automatically alert nominated staff in this experiment when the location or position of the road embankment changes exceeded predefined limits, while the post-processing scheme is executed to verify and analyse the real-time results.

To remove outliers and smooth the position estimates, several filtering methods with user-specified settings are applied as follows,

- Outlier filtering using the median, which takes 5 epochs to remove outliers from raw data.
- Weight Mean (WM), which uses a specified period of processed data and computes a weighted mean from the set of data and forwards only this average to the follow-on modules. A 2-hour sliding time window is applied in this experiment.
- Kalman Filter (KF) with four design assumptions: 1) No motion expected; 2) Highest accuracy; 3) Comparatively large delay of reaction to position changes; 4) The filter output converges.

In the experiment, the median filter will be applied before other data smoothing methods, such as the Weighted Mean or the Kalman Filter. Table 2 lists different data processing configurations in this experiment.

Analysis Name	Time delay (hrs)
RT-Internal Displacement Check	Real time
RT-BASE1-KF-Static	Real time
RT-CORS1-KF-Static	Real time
PP- BASE1-24Hour	24
PP- CORS1-24 Hour	24

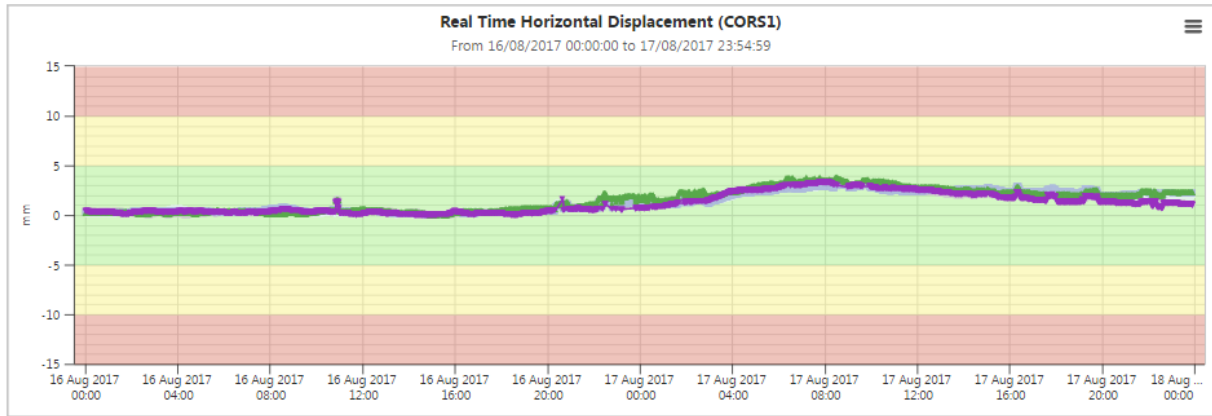
**Table 2.** Different data processing configurations in the experiment



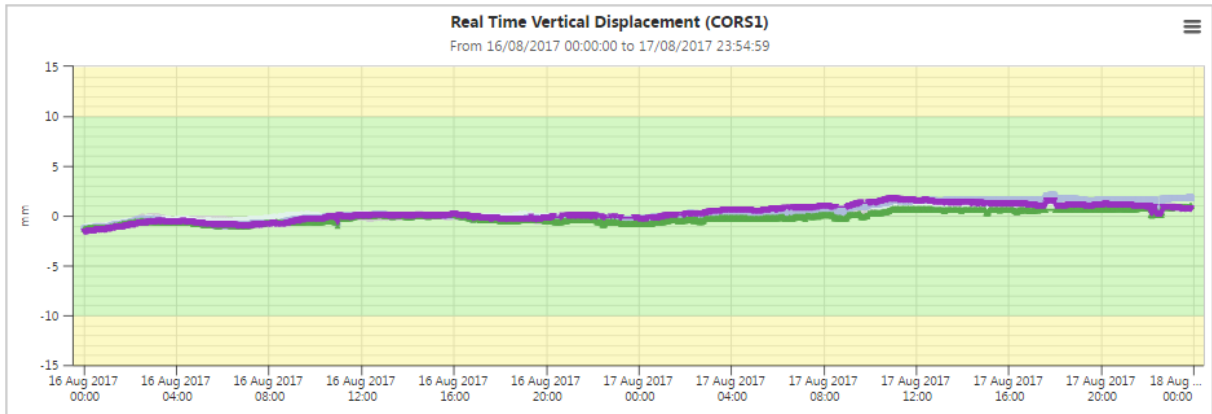
### 3.2 Real time positioning result

As mentioned in Table 2, the AGEDMS employs five strategies to process data in the experiment. For the sake of brevity, only the results applying the CORS1 reference station are presented here. The positioning statistics resulting from two stations will be listed later.

Figure 5 shows the 2D displacement time series of monitoring stations, which is calculated by the Kalman Filter with a no-motion design assumption. With the filtering option, the position result is smoothed, the variation of which is constrained within 5 mm. Figure 6 shows the monitoring station's reported vertical displacement variations, which are stable and less than 10 mm. Figure 5 and Figure 6 include two days of data. The multipath errors have been significantly reduced using the Kalman Filter.



**Figure 5.** Real time horizontal displacement of monitoring stations

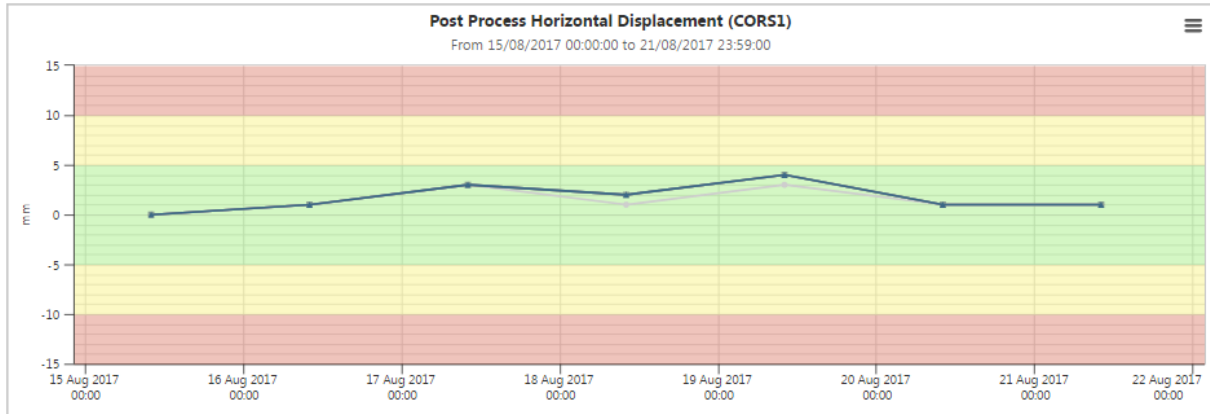


**Figure 6.** Real time vertical displacement of monitoring stations

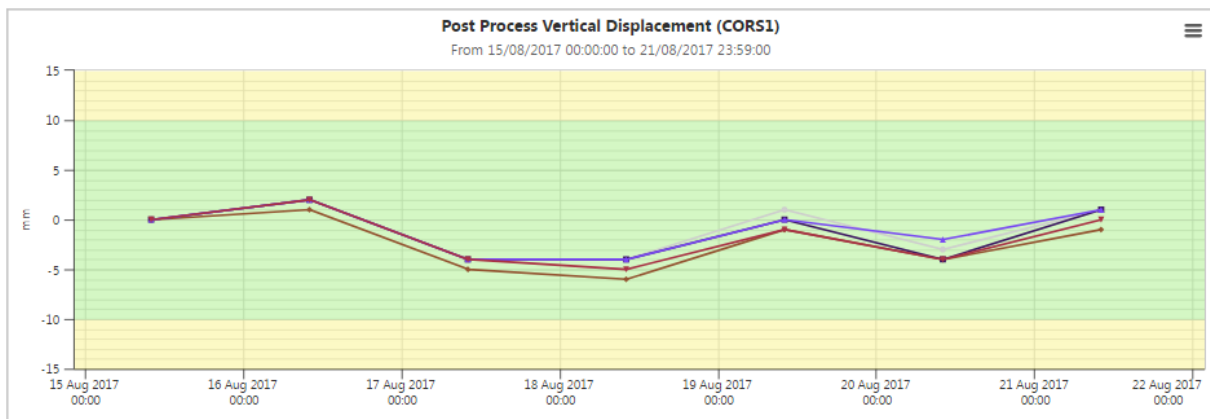
### 3.3 Post processing result

To verify and analyse the real-time positioning results, post processing over 24 hour durations and different reference stations was performed. The normal least-squares adjustment operator with median filter is applied to reduce the probability of the errors involved due to the same data processing algorithm. Figure 7 and Figure 8 show the post-processing 2D displacement and vertical displacement of monitoring stations for 7 day data, respectively. It can clearly be seen that the vertical variations are larger than the horizontal variations as expected, though they are still smaller than the predefined limit.





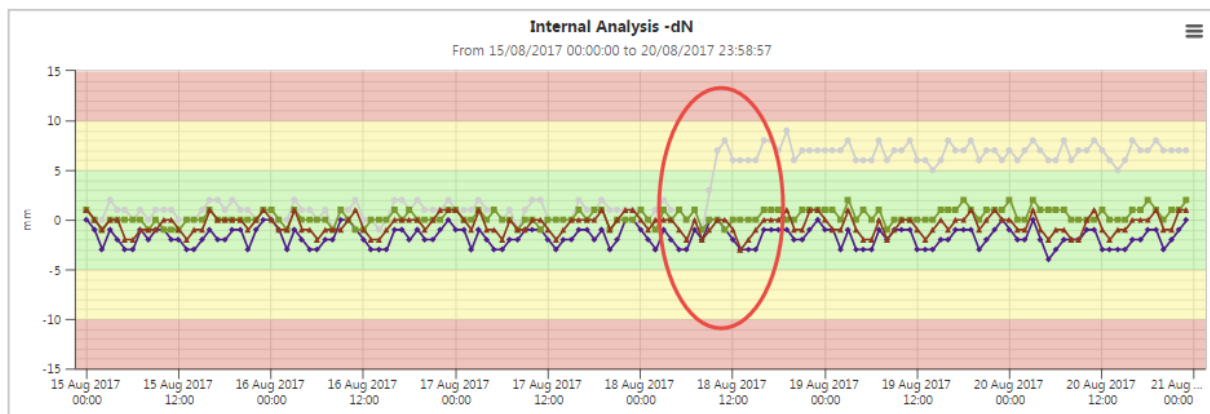
**Figure 7.** Post processing horizontal displacement of monitoring stations



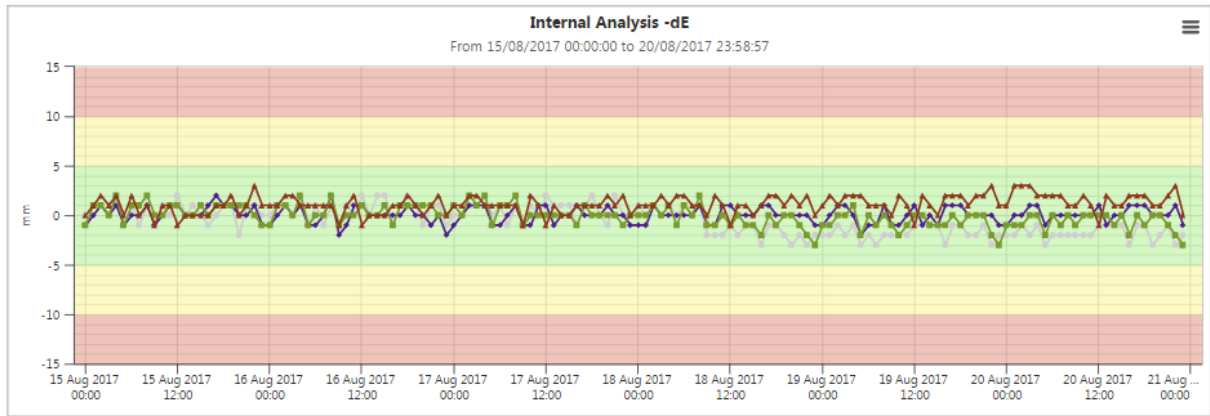
**Figure 8.** Post processing vertical displacement of monitoring stations

### 3.4 Movement detection

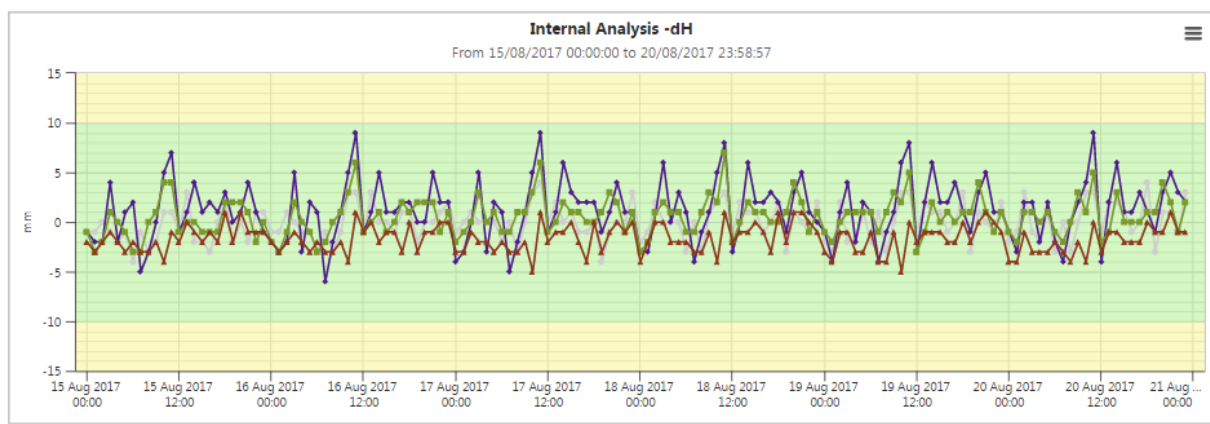
Figure 9 shows the reported northing displacement of GNSS receiver R9 0117 exceeded 5 mm on 18 August 2017 and remained over 5 mm since. All the baselines are less than 100 meters shown in Figure 4-2. Figure 10 and Figure 11 show the relative easting and vertical displacement reported by the other 4 GNSS receivers with R9 1360.



**Figure 9.** Real time northing displacement of monitoring stations



**Figure 10.** Real time northing displacement of monitoring stations



**Figure 11.** Real time northing displacement of monitoring stations

Table 3 summarises the statistical information in the experiment. The tabulated information is calculated from all the data recorded during the experiment, while the previous figures in this paper only show part of the results due to paper-length restrictions.

Analysis Name	3 $\sigma$ Northing (mm)	3 $\sigma$ Easting (mm)	3 $\sigma$ Height (mm)
Internal Check	3	3	6
RT-BASE1-KF-Static	2	2	7
RT-CORS1-KF-Static	1	1	6
PP- BASE1-24Hour	2	2	10
PP- CORS1-24 Hour	1	1	3

**Table 3.** Statistic information of different configurations in this experiment

## 4. CONCLUSIONS

Road embankments in Queensland have experienced large settlements since construction. Conventional geodetic techniques, e.g., Total Station measurement which require extensive manual work and much time, also increase the construction overhead. The AGEDMS has been developed to enhance safety alerting and risk management during the road embankment construction. The system performance has been evaluated in a real experiment area. The

experiment has demonstrated several key learnings for monitoring sudden and gradual deformation of embankments, which are summarised in the following.

- Employing geodetic or monitoring-grade GNSS antennas and receivers in base stations. It is also important to select a clear line of sight site and low multipath environments for reference stations. Applying high grade GNSS receivers and antennas in good observation environment and longer baseline length can outperform lower grade receivers and antennas even with shorter baselines.
- Optimal stable base station location close to the monitoring site. Establishing the base station as close to but outside of the deformation area can improve the position solution accuracy in both real-time and post processing modes. The base station should have a solid pillar foundation and a prescribed height with minimal thermal expansion properties and multipath interference.
- High precision monitoring solutions can be achieved. A horizontal SU of 3mm and vertical SU of 6mm can be achieved in real time when the baseline lengths don't exceed 200m. In terms of post processing, results are shown herein that indicate horizontal SU of 2mm and vertical SU of 4mm can be achieved for observation periods of 24 hours.
- Multiple base stations improve results accuracy and reliability. The presence of multiple base stations not only improves the positional accuracy, but also and more importantly enhances the AGEDMS reliability and integrity.

Previous AGEDMS systems employ high-grade dual-frequency receivers as monitoring stations. Herein, the authors have developed a more recent version of an AGEDMS that employs single-frequency receivers to achieve sub-centimetre position monitoring accuracy. Thus, this recent version of AGEDMS significantly reduces the total cost and can satisfy many other similar applications, e.g., landslide and structural health monitoring.

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