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Implementation of a successful geotechnical instrumentation & monitoring scheme in urban tunnelling project. – A case study of Forrestfield-Airport Link Project, Perth, Western Australia

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ABSTRACT: Instrumentation and monitoring is an integral part of any underground construction process. It helps to control excavation and verify design assumptions. A good monitoring program can provide safety against failure with early warnings and also provides legal protection to the designer and contractor. A critical requirement of the instrumentation & monitoring program is to present data in an accessible and meaningful graphical format on a real or near-real time basis to the stake holders, irrespective of their location across the world. The system should also be able to generate timely automated notifications through E-mail and/or SMS to stake holders in the event of exceedance of any control parameters for prompt application of remedial measures. This paper deals with the implementation of the geotechnical instrumentation and monitoring design of the Forrestfield-Airport Link Project in Perth, Western Australia, data management and presentation through a web based near real-time data management system.

1 INTRODUCTION

The Forrestfield Airport Link Project of the Public Transport Authority, Western Australia is an 8.5km extension of the existing Midland Line of Perth's rail-way network from Bayswater to Forrestfield and connecting Perth's Airport terminals. The alignment passes beneath interesting topographical features like the Swan River, and sensitive infrastructure such as the Suburb of City of Belmont, Airport Terminal Buildings and runway, as well as the Brookfield Rail network.



Figure 1: Alignment of Forrestfield Airport Link Project

Salini Impregilo - NRW Joint Venture (SI-NRW JV) is executing the Design Build Contract with Coffey being the instrumentation designer.

SI- NRW JV has entrusted Field Monitoring Services, Geomotion Australia, Land Surveys Joint Venture (FGLS JV) for the work of “Supply, Installation, Testing, Operation, Maintenance of Geotechnical and Survey Instrumentation, inclusive of monitoring and MIMS (Monitoring Information Management System) management for the project”. Geomotion Australia is working as a part of Joint Venture partner and broadly responsible for implementation of geotechnical instrumentation work and MIMS management for both geotechnical and geodetic monitoring.

1.1 Project

The project consists of approximately 7.1m dia. 7.14 km twin bored tunnel. The project has two dive structures, one at the Bayswater and another at Forrestfield. It also has two underground stations. The first is Redcliffe Station, which will connect Terminal 3 & 4 of Perth Airport. The second, is Airport Central station which will connect Perth's International Terminal 1 & Terminal 2. The at-grade station at Forrestfield shall serve as a terminal station of the alignment connecting to Kalamunda. The project also has three (3 no.) permanent emergency egress shafts.

All underground stations and dive structures involve construction of diaphragm walls. A mixture of bottom up and top down construction methods are deployed for these structures.

Tunnelling is done using two single shield tunnel boring machine which are both capable of deploying

slurry mode and earth pressure balance (EPB) mode depending on the geological condition along the alignment. Precast segmental lining is designed for permanent lining as a standard method for soft ground tunneling. Cross passage excavations are designed with lattice girders and shotcrete as primary support and in-situ reinforced cement concrete (RCC) lining as secondary support. However, ground improvement is designed in most cross-passage locations using jet grouting except for cross passages below the airport where ground freezing shall be utilized considering security and access restrictions at the surface.

1.2 *Geology along the alignment*

The geology along the alignment at the tunnel grade is broadly dominated by Perth Formation at the Bayswater end, Ascot Formation through the central section and Guildford Formation at the Forrestfield end.

Perth Formation is mainly paleochannel deposits in marine, estuarine and fresh water conditions and comprised of low to medium plasticity clay with some silt and sand. The upper unit of Perth Formation comprised of sand to silty sand. Ascot Formation is deposited in near shelf, near shore marine environment during multiple marine transgressions. It mainly comprises carbonate sand, sandy gravel and gravelly sand. Guildford Formation is deposited in fluvial environment and mainly comprises of stiff to hard low plasticity clayey sand and silty sand.

2 MONITORING REQUIREMENTS OF THE PROJECT

The broad requirements of the instrumentation and monitoring works are:

- Verify design assumptions;
- Provide confirmation of the predicted behaviour of the support system during excavation, tunnelling and other construction activities;
- Assess the effects of the project works and temporary works on existing condition of properties (As-set Monitoring);
- Enable construction to be carried out safely at every stage.

To meet these requirements, the contractor and de-signer of the project developed a comprehensive monitoring design. The geotechnical instrumentation and monitoring design can be divided into three groups:

1. Deep excavations of underground stations and dive structures (from where TBMs are launched and received) by constructing diaphragm walls.
2. Bored tunnels & cross passages, and
3. Asset monitoring - Instrumentation installed on adjacent properties to monitor the effect of excavation and tunnelling on these properties for safety of the structures.

The geotechnical instrumentation proposed in the project are as below:

2.1 *Deep excavation of underground station and dive structures*

- Multilevel vibrating wire piezometers to monitor changes in ground water pressure at multiple levels during excavation.
- Combined inclinometers with spider magnets to monitor lateral displacement and settlement/ heave of the ground associated with the excavation of underground stations and dive structures.
- Inclinometers in diaphragm walls to monitor lateral displacement during excavation.
- Spot weldable vibrating wire strain gauges in struts to monitor load
- Load cells in struts to monitor load
- Heave stakes to monitor heaving of the excavated surface between diaphragm walls

2.2 *Tunnel*

Tunnel Instrumentation can be divided into two sub-groups as below:

2.2.1 *Tunnel- surface instrumentation*

- Borehole extensometers (with single/multilevel anchors) on the top of the tunnel axis to monitor ground settlement/ heave during tunnelling.
- Vibrating wire piezometers to monitor changes in ground water pressure and levels during tunnelling
- Combined inclinometers with spider magnets to monitor lateral displacement and settlement/ heave of the ground associated with tunnelling

2.2.2 *Tunnel- segments*

- Vibrating wire strain gauges installed in precast tunnel segments to monitor change in strain in the tunnel segments during tunnelling as well as cross passage excavation.

2.3 *Asset monitoring along the alignment*

- Biaxial tiltmeters and beam sensors (uniaxial) to monitor the displacement of the existing structures.
- Vibrating wire strain gauges to monitor the deformation of structures caused by excavation/ tunneling
- Vibration monitors with triaxial geophone sensors to monitor and limit the extent of vibration effect on adjacent structures due to construction.

2.4 *Monitoring review level (MRL)*

The Geotechnical Manager assigns monitoring review levels to every instrument installed and

presented in MIMS. There are three types of review levels; trigger, design and allowable.

Trigger levels are 70% of the design value. Design levels are the best estimate of the ground/building movement calculated based on contractor's design parameter. The allowable levels are maximum or minimum (upper or lower) allowable readings as defined in the design specification of the contract.

Trigger levels are shown in the MIMS and system generated automated alarms are sent to stakeholders through e-mail and SMS should these trigger levels exceeded.

3 IMPLEMENTATION OF GEOTECHNICAL MONITORING DESIGN

To implement the monitoring requirement Geomotion deployed a highly experienced team of engineers and technicians for installation and monitoring of the geotechnical instruments. This involves drilling and installation of instruments listed in section 2 as per the approved installation procedure. To date, 2838m of drilling has been performed. The key for the successful installation of the instruments are close coordination and planning with the contractor's geotechnical, construction, tunnelling team and stake holders.

The major tasks are:

- Installation of geotechnical instruments in-line with contractor's construction program;
- Installation of data loggers and establishment of telemetry for automation of critical instruments for near real-time monitoring.
- Daily/weekly manual readings, data check and uploading of web-based Monitoring Information Management System (MIMS)
- Routine inspection and maintenance of the instruments against possible damage due to construction activities.

The table below shows the quantities of instruments installed in the project.

Table 1. List of Total Instrumentation installed till August,18.

Instrument Installed as on August, 2018	Qty
In-Place Inclinator (including DEX-S)	56
Single-Point Rod Extensometer with displacement Sensors	48
Multi-Point Rod Extensometer with displacement Sensors	18
Biaxial Tilt Meters	15
Strain Gauges (Surface)	24
Strain Gauges (Tunnel Segment)	372
Strain Gauges (Spot Weldable- Strut)	18
Load Cell (Strut)	10
Diaphragm Wall Inclinator Tubing, in metre	727
Combined Inclinator -Extensometer Tubing (soil), in metre	1162
Vibrating Wire Piezometer	89
Vented Pressure Transduce (in open standpipe)	13
Beam Sensor	5

Heave Stake	2
Vibration Monitor	7

Since the alignment is passing under the airport, existing buildings, highways and railway networks, state of the art wireless technology has proved to be the best solution for automatic data acquisition and transfer of data to a cloud based elastic virtual server. Wireless link eliminates all cabling between the individual sensors to the MIMS. To do this, several technologies have been implemented.

3.1 Radio communication technology using loads sensing G6 loggers

- The Project alignment is divided into four sections and a Load Sensing (LS) Gateway installed at each section namely Forrestfield Dive, Airport Central Station, Redcliffe Station and Bayswater Dive so that LS Nodes (data loggers) connected to any sensor along the alignment can communicate with one of these centralized Gateways
- Installation of LS G6 Nodes to the critical instruments such as piezometers and displacement transducers attached to single/ multiple rod extensometers which require near real time monitoring.

Figure 2 shows the how the wireless link works. Individual nodes transfer data to a centralized gateway using radio communication technology and thereafter the Gateway transfers data to the cloud-based server using a cellular network. The MIMS then picks up the data without any human interference.

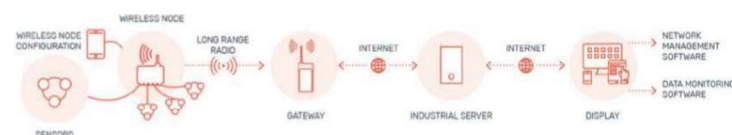


Figure 2: working principal of LS Node & Gateway to web-based monitoring system

3.2 Mini Omnia log data logger

The Sisgeo Mini Omnia log is a 4-channel datalogger with vibrating wire built-in interface. It has a GPRS on-board modem which enables data to be pushed onto the cloud-based server. Mini Omnia loggers have been installed mainly with Vibrating Wire strain gauges in tunnel segments and the level beam sensors on the project.

3.3 Omnia log data logger

The Sisgeo Omnia log has a Web & FTP server on board with 8 analog channels, expandable to 392 channels and 2 digital opto-isolated input ports.

Omniolog data loggers have been used when a great number and variety of sensors are to be read automatically in any monitoring array and transferred to the cloud-based server using 3G based telemetry. Reference is drawn from figures 3 and 4.

3.4 Typical array design

Standard array types were repeated along the tunnel alignment and excavations.

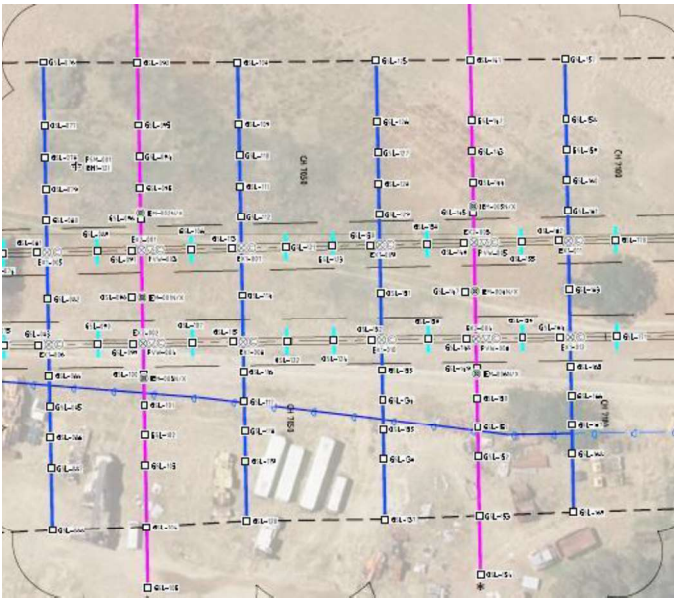


Figure 3: Instrumentation Design at Tunnel section (Plan)

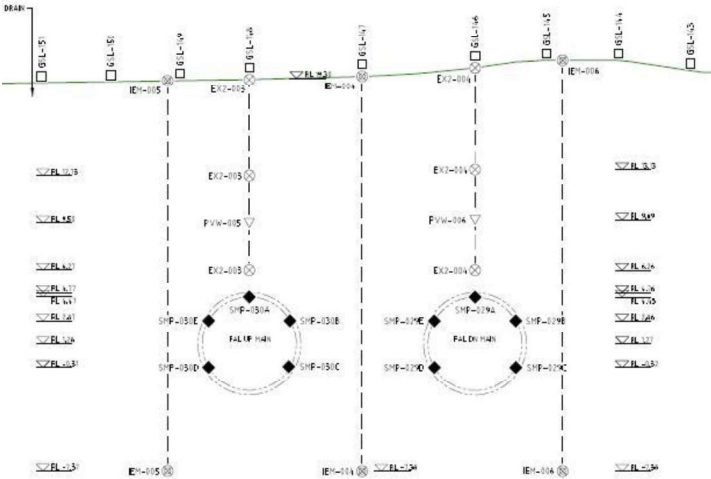


Figure 4: Design of F array (section)

The F (pink colour array in figure 3) monitoring arrays comprise of three combined inclinometer extensometers and two multi rod extensometers with piezometers. Each combined inclinometer-extensometer is installed with five to seven in-place inclinometer DEX-S probes. These probes provide both horizontal movements (X, Y-axes) and vertical settlement (Z-axis) for automatic 3-D borehole profile monitoring. The E (blue colour in figure 3) monitoring arrays comprise of single point rod extensometers. All these

sensors are connected to Omniologs for automation and near real time monitoring.

4 DATA MANAGEMENT AND PROCESSING

The monitoring information management System (MIMS) is delivered to the project by Geomotion in collaboration with Maxwell Geosystem Limited (MGS). The MIMS uses MGS’s MissionOS which utilises Amazon Web Service’s elastic web server to manage increasing data volume and uninterrupted processing requirement. A separate FTP data server is used to accept incoming raw data from the dataloggers. All automated data is collected and stored on the dataloggers, transferred to a cloud-based FTP data server using telemetry and then imported into the MIMS database. The backup of the data server is taken at a stipulated time every day.

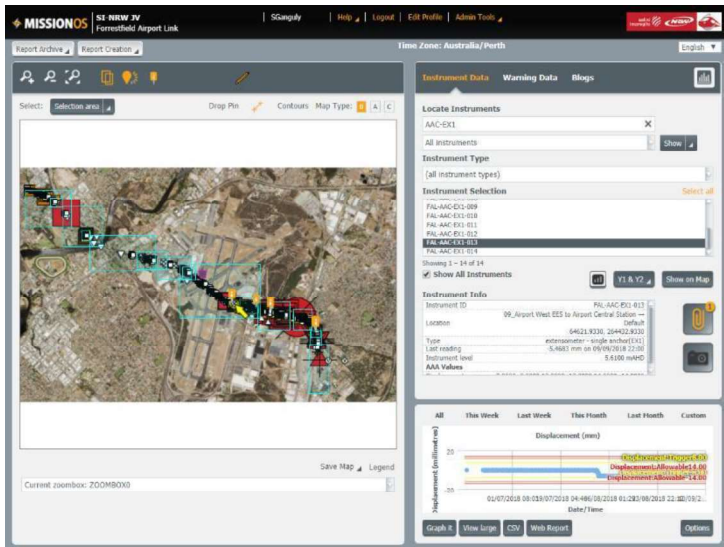


Figure 5: Web-based monitoring information management system (MIMS)

4.1 User setup

The system allows for 4 different types of user, typically providing the following permissions:

- Viewer – can access data for assigned project areas.
- Editor – as above and can edit project configuration and data.
- Approver – as above and can approve manual in-pu t data.
- Admin – access to all areas of the system, can create and edit users and project sites.

These users can be customized to add or restrict certain areas of access.

4.2 Automated readings

For data processing of automated readings each file that is automatically transferred to the system has a configuration setup. This allows the acceptance of

any text file type in Mission OS so that different dataloggers and instrumentation can be used. The critical instruments of the project are monitored using auto-mated dataloggers and telemetry.

5 OUTCOME OF RELIABLE DATA REPORTING

The near real time presentation of monitoring data has helped the engineers and consultants verify the design assumptions and make necessary changes in design to control ground movement.

For example, near real time subsurface settlement data of single point extensometers installed 1.5m above the tunnel crown, as presented in Figure 8, assisted the contractor and consultants to review and ad-just the face pressure & grout pressure requirement of TBM for encountered geological condition.

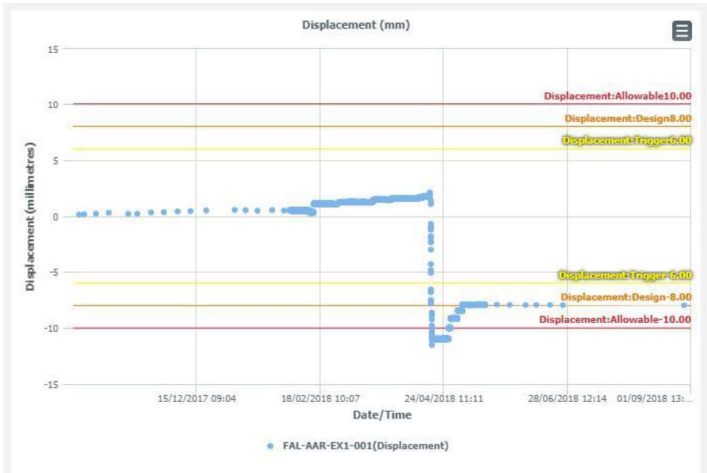


Figure 6: Automated readings of a single point rod extensometer at Airside with MRL’s using wireless link

4.3 Manual readings

The system also accepts manual data from any type of instrument. Manual data can be uploaded through the portal directly or through the proprietary Generic Data Loader (GDL). During manual data upload the user is prompted if there are any alarms that will be triggered from the readings. This helps in stopping human error being introduced to the manual recording of data.

Figure 8: Near real time borehole extensometer data collection and presentation in the MIMS with automated alarms to all stakeholders in exceedance of trigger values during TBM drive

Similarly, the precise inclinometer data at Redcliffe Station installed inside the diaphragm wall as presented in Figure 9 below shows progressive lateral movement of the ground during excavation.

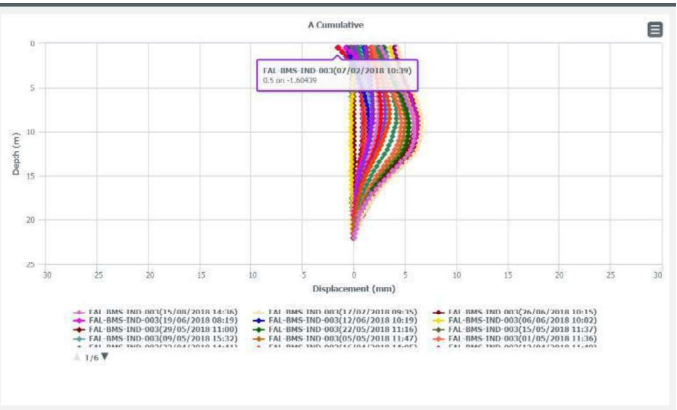
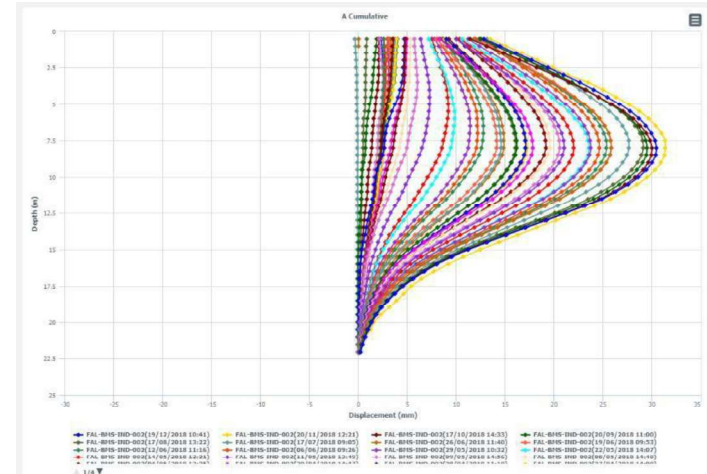


Figure 7: Manual readings of an inclinometer inside the diaphragm wall at Redcliffe Station

4.4 Automated overdue data alert

The monitoring frequencies as required by the design can be set up in the MIMS. The system is capable of generating overdue data alerts to the user in case there is a missed data points and not uploaded in the MIMS based on the frequencies already set up. This assists users to monitor the status of the data acquisition and/or functionality of the automated logging system.

Figure 9: Manual inclinometer data presentation of Redcliffe station

The system also sends the alerts to the users when an overdue data point is uploaded in the system to confirm the process has been completed.

Delivery of actionable data in a near-real time context allows designers to implement the contingency

measures in adverse/uncontrollable conditions within a short timeframe.

6 CONCLUSIONS

Good planning and proper selection of cost-effective monitoring technology together with installation by experienced and knowledgeable staff can lead to successful implementation of a monitoring design of any critical and high-risk urban tunnelling project. Precise data acquisition and near real time presentation is the key for owner, contractor and consultants to make timely decision and verify design performance of the project.