Slope monitoring and data visualisation state-of-the-art – advancing to Rio Tinto Iron Ore's Mine of the Future™

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Abstract

Rio Tinto Iron Ore's (RTIO) Western Australian mine operations comprises 14 mines with a centralised 'Mission Control' Operations Centre (OC) in Perth, and currently delivers 237 Mt/a ore from over 120 individual open pits. Operational challenges in terms of implementation of effective slope monitoring systems with appropriate visibility of system health and alarm notifications needed to be addressed. The geotechnical, management and support teams are site and Perth based, and all require access to geoscience monitoring data.

Historically, each site had an independent monitoring and alarming systems. Transparency of monitoring data, health checks and alarming capabilities were limited. The lack of a system to display temporal geotechnical (slope performance), and hydrogeological monitoring data, with 24/7 alarm and system health status had been identified as a 'gap' following a previous slope instability incident at one of the Pilbara Operations.

At project inception, the need for a visualisation and management tool which had a multidisciplinary focus and integrating georeferenced geoscience monitoring data with physical models in near real time, was identified. Consequently the Geoscience Monitoring Data System (GMDS) was developed to address three main requirements:

- *Provide a consolidated overview of all geoscience monitoring data and physical models.*

- *Show monitoring system and device health, and alarm status at a high level.*

- *Be integrated with existing slope performance and hazard management systems.*

This tool is in alignment with Rio Tinto's Mine of the Future and RTIO's Operations Centre vision by using technology to reduce costs, increase efficiency and improve health, safety and environmental performance. It provides the functionality to manage diverse instrumentation data in a consistent, standardised approach to support RTIO's geographically spread expansion plans.

1   Introduction

Rio Tinto Iron Ore (RTIO) mining operations are located in the Pilbara Region of Western Australia, approximately 1,000 km north of Perth (Figure 1). They comprise 14 iron ore mines and three port facilities, supported by 1,400 km rail network. In 2009, 170 million tonnes were produced from the 100 operating pits increasing to 237 Mt/a from over 120 pits in 2013. Orebodies comprise multiple ore pods, resulting in multi pit mines, where a number of pits can be active at one time (depending on product quality requirements). Most mines have site based geotechnical engineers with support from Perth geotechnical teams.
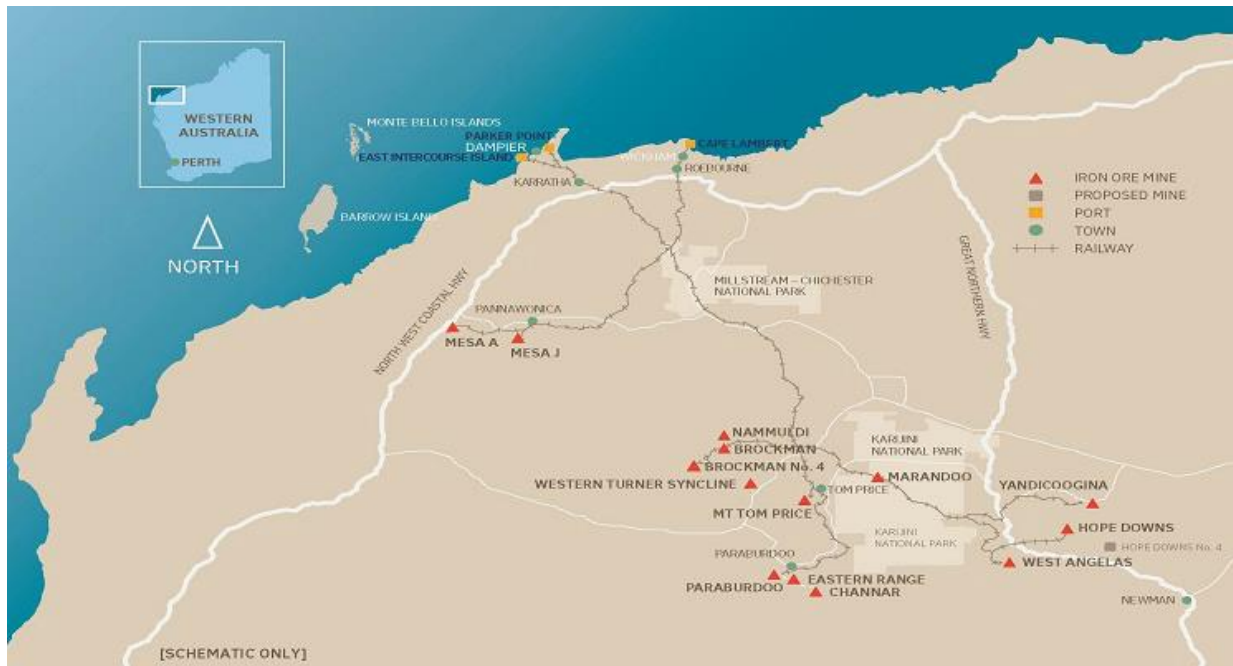
Figure 1 Rio Tinto Iron Ore operations in the Pilbara, Western Australia

2 Background

Prior to 2008, the geotechnical risk management at the RTIO Operations in the Pilbara was site based. Most operations had a site geotechnical team responsible for the routine geotechnical risk management. The skill and experience of geotechnical teams across the Pilbara varied and most geotechnical engineers had less than five years of experience. The situation was further exacerbated by the Australian mining boom, resulting in a scarcity of qualified and experienced geotechnical engineers, limited across site support, and lack of standardisation of systems and tools.

Monitoring systems comprised mainly manual survey prism monitoring, with few automated systems in place. Near real time monitoring was limited, and slope monitor alarming restricted to email and SMS alerts. This resulted in variable levels of geotechnical risk management across the different operations.

Since 2007 RTIO has commissioned five new mines and ramped up production. An Operations Centre (OC) was established in Perth and all the pit, plant and train controllers from the mine operations were moved into a single control room in the OC. Improvements and increases to the geotechnical resources were made to keep up with this increased production from the Pilbara operations. A Technical Services Geotechnical Assurance group was established to provide across site support and be responsible for the development and commissioning of standardised tools and systems to assist with Geotechnical risk management in the Pilbara.

Initially each monitoring system had separate tools to interrogate and analyse data; with individual system health checks. The risk with this approach was that without a single point of reference and transparency of the monitoring system status; the potential existed for system component failure and/or critical changes in instrument response to be overlooked, leading to inadequate slope management.

Slope instability in early 2010 highlighted the need for improved geoscience monitoring systems, with clear recommendations for improvements in monitoring capabilities and alarm functionality. Continuous (24/7) system health and availability checks, and better data visualisation was needed to enhance interpretation, analysis, management and communication of slope monitoring data. Monitoring system and alarm functionality improvement were prioritised and were addressed during 2010 and 2011. This included OC alarming capability, expanded Slope Radar fleet and increased automated survey capabilities.

A system providing a high-level overview of Geoscience monitoring data, monitoring system health and alarm status was required. The development of this system is the focus of this paper.

3 Challenges

The expansion of slope monitoring systems and tools brought about a number of challenges:

- The number of automated prism monitoring systems increased from three to 13 and the quantity of data increased as survey intervals changed from days to hours.

- Increased below water table mining required more piezometers systems.

- New monitoring devices, such as Time Domain Reflectometry (TDR), resulted in an increase in data that needed to be analyses and managed.

- Limitations associated with reliance on proprietary vendor alarm notification systems (i.e. dependence of single systems with limited redundancy and limited business resilience support).

The relocation of pit controllers to the OC in Perth resulted in no onsite capacity for 24/7 monitoring of slope alarms. Where near real time monitoring and alarming was required special arrangements had to be made to ensure the ongoing monitoring of slope alarms. These temporary solutions were not sustainable.

It was clear that a more structured approach was required to ensure transparent, auditable and sustainable geotechnical risk management.

4 Monitoring framework

Slope performance monitoring is an integral part of effective slope management. It not only provides a safe working environment, but also provides important slope performance evidence for the calibration and optimisation of designs.

The most important purpose of a slope monitoring programme is to: (1) maintain safe operational practices, (2) provide advance notice of instability and (3) provide additional geotechnical information regarding slope behaviour (Sjöberg, 1996).

Monitoring is routinely adopted in the mining environment to manage the residual risk associated with uncertainty in design. Even the most carefully designed slopes may experience failure from unknown structures, unexpected weather patterns or seismic shock (Girard and McHugh, 2000).

Marr (2005) and Sullivan (1993) provide more detailed discussion on the objectives and planning of monitoring programmes. A useful reference for the methods and monitoring requirements for open pit applications in relation to the type and scale of the mine slopes being considered is provided by Hawley et al. (2009).

Key elements of a well designed monitoring system include:

- Early detection of potential incipient instability.

- Communication of alarm exceedance.

- Analytical functionality in assessing current conditions and estimation of forecast predictions.

- Confirming physical characteristics are within expected/required performance range (deformation, pore pressures, etc.).

The timely availability of monitoring data, analysis and appropriate response is critical to maintaining a safe operating environment while maximising ore recovery. A risk based approach was introduced to manage geotechnical risks in the expanding Pilbara operations and ensure appropriate controls were implemented commensurable with the acceptable risk.

A formalised risk assessment tool, Geotechnical Risk and Hazard Assessment Management System (GRAHAMS), was developed to assess and document the safety and economic risks of all slopes. Each risk assessment considered the expected modes of instability, slope geometry, design recommendations and personnel/equipment exposures. The risk assessment forms the basis of a multi-layered approach whereby the monitoring is dependent upon on the risk level. Lower risk slopes are monitored with basic monitoring systems, e.g. visual inspections. As the risk profile increases the level and frequency of monitoring is escalated to ensure improved data accuracy and near real, and alarmed, monitoring. The RTIO risk-based monitoring approach is summarised in Figure 2. The monitoring system is an integral part of the geotechnical Trigger Action Response Plan (TARP).
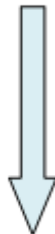
Slope Risk	Monitoring Method	Monitoring Frequency	Access Required
Low Risk	Berm inspections (crack inspections)	Increasing monitoring frequency (some can be alarmed if appropriate telemetry & alert systems are in place)	Access to berms
Low Risk	Manually read crack monitors or surface extensometers	Increasing monitoring frequency (some can be alarmed if appropriate telemetry & alert systems are in place)	Access to berms
Moderate Risk	Laser scanners		Access to berms (install/maintenance)
Moderate Risk	Inclinometers		Access to berms (readings)
Moderate Risk	TDR/VWP		Access to berms (readings)/Telemetry
Moderate Risk	Automated surface extensometers		Access to berms (readings)/Telemetry
Moderate Risk	Manually read prisms		Initial access to berms (install targets)
High Risk	ATS Prisms (Automated Total Station)	Requires near real time telemetry and alarms (i.e. Alert, Alarm, Evacuate)	Access to berms (install/maintenance)
Critical Risk (Safety Critical Monitoring)	Radar		Remote
Critical Risk (Safety Critical Monitoring)	Automated surface extensometers with local or remote alarms		Remote

Figure 2 The RTIO risk-based hierarchical approach to slope monitoring

4.1   Primary monitoring systems

Prism and radar monitoring are the primary quantitative slope monitoring tools used by RTIO. These sophisticated tools require input from specialised Pilbara and Perth based teams to implement, operate, and support. Detailed Guidance Notes provide information on the RTIO standardised technical approach to the management and operation the various monitoring systems. A RACI (Responsible, Accountable, Consult, Inform) matrix is included in the guidance notes to ensure clarity on areas of responsibility and accountability. This matrix provides a breakdown of roles and responsibilities for related tasks:

- The accountable person is to ensure that the task is carried out – 'the buck stops here'.

- The responsible person is the 'doer' who carries out the work.

- Consult refers to a person that is required to provide input or guidance and involves two-way communication.

- Inform refers to one-way communication and indicates which stakeholders should be kept informed during the process.

Both manual and automated prism monitoring systems are utilised. Measurement frequencies are adjusted to provide sufficient reliability of data depending on the risk level. The prism monitoring systems have been consolidated into a standardised platform to accommodate the growth in monitoring requirements associated with production ramp-up. This also provided a consistent basis for development and engagement of system support and maintenance.

RTIO has a number of slope monitoring radars: dedicated radars are deployed on mine operations with a higher geotechnical risk as identified during the risk assessment process. The RTIO geotechnical risk assessment tool is used to evaluate the shorter term deployment requirements of the roving radar fleet (i.e. prioritise the business risk). The slope radars are utilised for three different levels of monitoring depending on the risk:

- Critical monitoring: Critical monitoring is normally undertaken in high risk areas. This level of monitoring requires near real time monitoring and 24/7 alarm monitoring and is mandatory to be in place while mining operations in the area continue.

- Diagnostic monitoring: Diagnostic monitoring is typically applied in moderate risk areas, but can be employed in any area. Monitoring may include near real time monitoring and 24/7 alarming.

- Background monitoring: Background monitoring is the baseline monitoring that is employed on all pit slopes, specifically low risk slopes. This monitoring is normally done with prism monitoring and the frequency can vary. Although the slope radars are not normally used in these circumstances, they can be deployed where limited or no prism monitoring is available.

4.2   Other monitoring

Other supplementary slope monitoring methods include Time Domain Reflectometry (TDR), surface wireline extensometers (or crackmeters) and inclinometers in specific circumstances.

Most Pilbara slope instabilities are structurally controlled and occur as a result of sliding on shale beds often with side release on faults or dykes. TDR cables have been used to monitor sub-surface displacement. The magnitude of shear is not quantified but the depth of shear along the cable is defined. This information is helpful to assist with the interpretation of monitoring results, and providing early warning of dilation of structures. TDRs may be manually read or downloaded via the telemetry network. This enables automated acquisition of data and also links to the Geoscience Monitoring Data System (GMDS). TDRs were installed as part of the remediation plan of a significant instability at one of the Pilbara operations (Joass et al., 2013).

Surface monitoring (prisms, slope radar) data are complimented by manual and automated wireline extensometers. These are installed where cracks or other surface expression of instabilities are observed. In most cases these are temporary installations to obtain an early indication of possible movement. Longer term installations, or where critical monitoring is required, are linked to the telemetry network to provide near real time monitoring and alarm notification.

5   Perth operations centre

RTIO commissioned the revolutionary Operations Centre (OC) near the domestic airport in Perth in 2009. The OC is 'mission control' for the entire RTIO Pilbara network of mines, rail networks, port terminals and power and other infrastructure. The OC provides control and enables the execution of integrated planning and remote technical support helping optimise mining operations end to end. A key element of the OC function involves better identification of performance issues across the iron ore business – geotechnical slope performance alarm notification requirements align with this objective. The OC provided an ideal opportunity to improve the geotechnical alarm notification process and leverage off the available business critical systems and support. Business resilience systems associated with a remote operations centre, such as communication system redundancy and contingency planning, are not often available to geotechnical monitoring systems on a stand-alone mining operation. These were now part of the standard monitoring system.

6   Alarming

Automated prism and radar monitoring systems are alarmed at all the RTIO operations. Historically the prism alarms would be communicated through emails and SMS texting to mobile phones. None of these were considered reliable or robust; incidents were recorded where alarms were not received. Radar alarms

were monitoring by the pit controllers on site. To ensure ongoing 24/7 alarm surveillance the prism and radar alarm monitoring had to be communicated through the OC.

The most effective way to integrate the slope alarming to the OC was to link to the Modular Dispatch® system. With the assistance of the various radar and automated prism vendors, the monitoring system software was modified to send alarm notifications to the pit controller via the Modular Dispatch® network. Alarms are displayed as an 'exception message' on the pit controller's screen. This message must be acknowledged and the actions taken recorded to free up the Dispatch® screen. This ensures that alarms are acknowledged and actioned. A health check has been designed into the system whereby any system failure will result in a Grey Alert being triggered. This health check also monitors the communication between the monitoring device, the vendor software and the OC. The pit controller reports all alarms and alerts to the pit supervisor, who then implements actions in accordance with the site TARP.

7   Telemetry

Telemetry is used for transfer of monitoring data to produce timely data analysis and minimise exposure of staff to pit slope hazards. A standardised Pilbara operations telemetry system was developed in conjunction with RTIO's Information System and Technology and Production Systems teams. Data from various monitoring devices are transmitted via telemetry to respective databases. Telemetered monitoring devices further allows for the systems to be alarmed. Improved confidence in slope performance data allows design optimisation opportunities and allows potential impacts on production to be identified earlier.

8   Data management and visualisation

The ongoing personnel time commitments required in managing monitoring programmes is often underestimated. Data processing, validation, presentation and analysis can be a daunting laborious task if robust systems and data bases are not in place to efficiently assist with this important work. Timely completion of these tasks underpins the safety objectives of most monitoring programmes. Jooste and Cawood (2007), Marr (2005) and Hawley et al. (2009) all highlight the importance of timely and reliable data which must be evaluated and acted on quickly.

The increased availability and volume of near real time monitoring data brings new challenges in managing this data flow and converting this data into information upon which informed engineering judgements can be made. Data represents a set of discrete (unprocessed) facts about events (e.g. VWP pore pressure readings for a month). Data are converted to information by providing context and aggregation of processed data which makes decision making easier (e.g. VWP pore pressure graph for the west pit McRae shale unit, showing daily rainfall and dewatering pumping rates). A clear focus and understanding of the monitoring objectives is essential to decide on the nature and volume of data that is required for creating the necessary information.

Typically a range of devices are used in mine slope monitoring, these monitoring systems have separate proprietary software to interrogate and analyse data. The risk with this approach is that without a single consolidated point of reference for monitoring system and alarm status; the potential exists for system component failure and/or critical changes in instrument response to be overlooked, leading to inadequately managed slope instability (i.e. unanticipated, uncontrolled slope failure) with potential significant safety and economic consequences.

The significance of the spatial interrelations between expected/planned physicals (geology, geotechnical and hydrogeological models, slope design) and actual slope performance demands that a consolidated overview of geoscience monitoring data is available to support active risk management. Planning, deployment and management of monitoring systems must take into account these spatial dependencies and controls.

Over the last three years RTIO has made improvements in monitoring systems, data acquisition (telemetry) and continuous (24/7) system health and status checks. A consolidated system for rapid reporting and data

visualisation was needed to enhance interpretation, analysis, management and communication of slope performance monitoring data. The intention was not to develop full functionality of data analysis for all instrumentation data types, rather provide a summary overview of current data status. This could include a summary of last six to 12 months data, updated in near real time presented in standardised format e.g. prism data showing: displacement vectors, rates of movement available through the visualisation tool. If detailed analysis is warranted, such as determination of appropriate alarm thresholds or carry out inverse velocity calculations, the proprietary software would be utilised.

A project was initiated in 2010 to investigate available tools to meet the following business requirements:

- A standard platform that could work effectively across the 14 mine sites in the Pilbara and capable of managing geotechnical, hydrogeological and metrological data.

- Compatibility with existing geoscience data bases and information (acQuire, EnviroSys and Vulcan) by integrating georeferenced monitoring data with physical models in near real time.

- Provide a centralised repository for georeferenced geoscience monitoring data.

- Present monitoring data along with mine design, drillhole and geological model data as well as geotechnical inspection, mapping, risk, hazard and fall of ground areas.

- Provide flexibility in terms of the devices and data that can be aggregated.

- New devices must be able to be easily added to the system and data collected from the proprietary data systems.

- Device agnostic, i.e. able to manage diverse instrument types and be unrestricted by vendor.

- Provide a flexible front-end visualisation interface to allow the information to be visualised in a variety of ways.

This approach enabled the existing RTIO Google Maps and Google Earth Enterprise (GEE) systems to be effectively leveraged for visualisation of the geotechnical data, since terrain and imagery for most sites already exists in the RTIO GEE system. The system can also be shared with other Rio Tinto business units. New operations can be easily integrated into this environment, as they will be able to either use the existing Google Earth Enterprise system from RTIO, or put in place their own GEE system by building on the experience already developed by RTIO.

9   Geoscience monitoring data system (GMDS)

At the time of development, there was a gap in appropriate commercially available geoscience monitoring data visualisation and management tools suitable to fulfil RTIO system requirements. The available systems were proprietary geoscience monitoring system tools that were merely repositories of temporal data, and had no or limited spatial representation functionality. Those that did have spatial functionality were typically civil engineering centred and were restrictive in the type of instruments supported (i.e. vendor specific, and no slope radar functionality) and were not suited to the dynamic conditions required for mining applications.

Rio Tinto's Kennecott Utah Copper Corporation (KUCC) had developed a prototype for the needs of a single site and the devices and systems in place at that operation. This system was demonstrated at the Rio Tinto Geotechnical Forum in 2010, and was quickly identified as a forerunner of the concept of aggregating data from heterogeneous monitoring devices. This geographical information system (GIS) was limited to 2D representations of data, but nevertheless presented the best starting point to develop an engineered solution with the intent of becoming a flexible and robust system for general mine operation use. A team of in-house specialists, with technical expertise in the sophisticated 'mine of the future' systems, collaborated with external developers to develop a full 3D geoscience monitoring management system for RTIO. It was tailored for mining applications; capable of supporting diverse surface and sub-surface monitoring data,

providing near real time reports on system health, alarm status and individual component availability capabilities. The engineered system consists of the following major components as outlined in Figure 3:

- Device connectors/plugins for accessing data from vendor data stores (telemetry):
    - Prisms.
    - Radars.
    - Crackmeters.
    - Vibrating Wire Piezometers.
    - Time Domain Reflectometry (TDR) cable.
    - Weather station data.
    - Georeferenced photographs.
- A common aggregation database (SQL).
- Services for data inquiry, translation, and visualisation.
- Interfaces for visualisation systems (Google Maps, Google Earth, VirtualEYES).
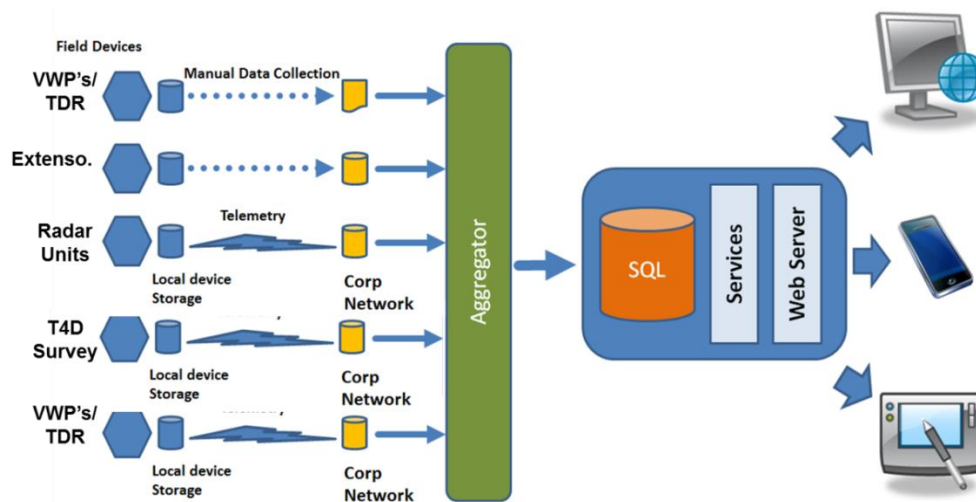
Figure 3 GMDS data flow

This system provides a single point of access for an integrated view of the geotechnical monitoring without having to access each of the individual vendor systems. The aggregation and standardisation of the data allows for easier evaluation of monitoring information and also facilitates communication of alert and system health status through the 'Manager's Dashboard' (Figure 4). This feature allows technical and non-technical users to readily identify components of the monitoring system which are not performing as expected, resulting in an increased slope risk. The timely availability, analyses and response to this information is critical in maintaining a safe operating environment.

The 'Manager's Dashboard' (Figure 4) shows an overview of the monitoring status in the Pilbara, reporting the alarming and health status of each mine. By navigating the GEE maps, it is possible to drill down into each site more detail can be viewed for different monitoring systems or mining areas (Figure 5). These mine maps can be overlain with either monitoring information or geoscience models/information (structural data, geology), or both monitoring and model information. Data from various devices can be graphed as shown in Figure 6, also incorporating meteorological information. Information from more than one monitoring device can be viewed in one graph. A selection tool allows the user to interactively select the monitoring device on the image.
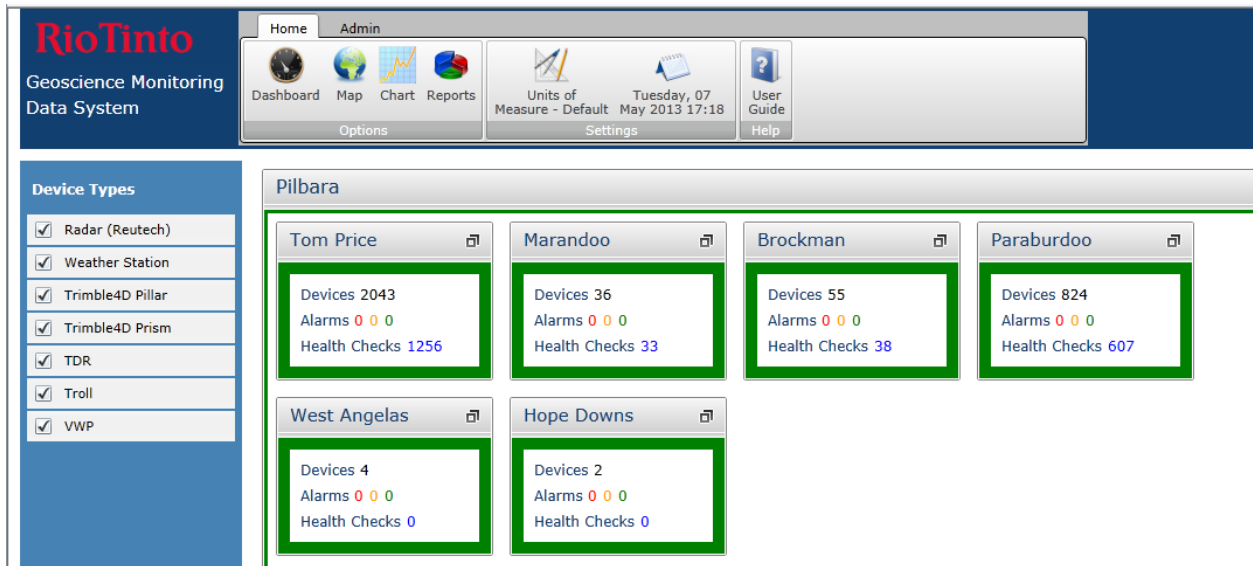
Figure 4 Manager's geoscience monitoring data dashboard

The web based tool allows for easy (permissions based) sharing of monitoring data, particularly for Technical Assurance purposes in reviewing data at the request of operations, or in terms of providing routine oversight of data and systems management. External and internal (such as Rio Tinto's Technology and Innovation (T&I) group) consultants may have this functionality to provide expert opinion on specific data sets, or to support remote operations.

Once fully implemented, such a system will revolutionise the way that technical advice is delivered to our sites, providing near real-time, online mentoring and advice on situations of concern, reducing the need for some travel, and improving our ability to manage the impacts of slope movements on our people and operations.
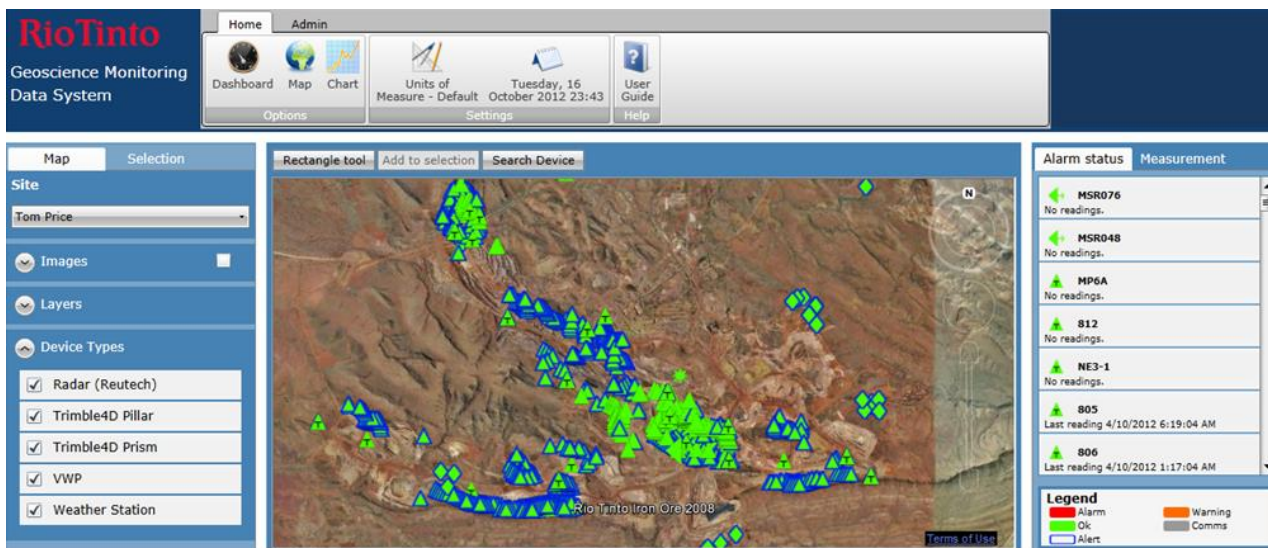

Figure 5 GMDS overview of Tom Price monitoring devices and alarm status
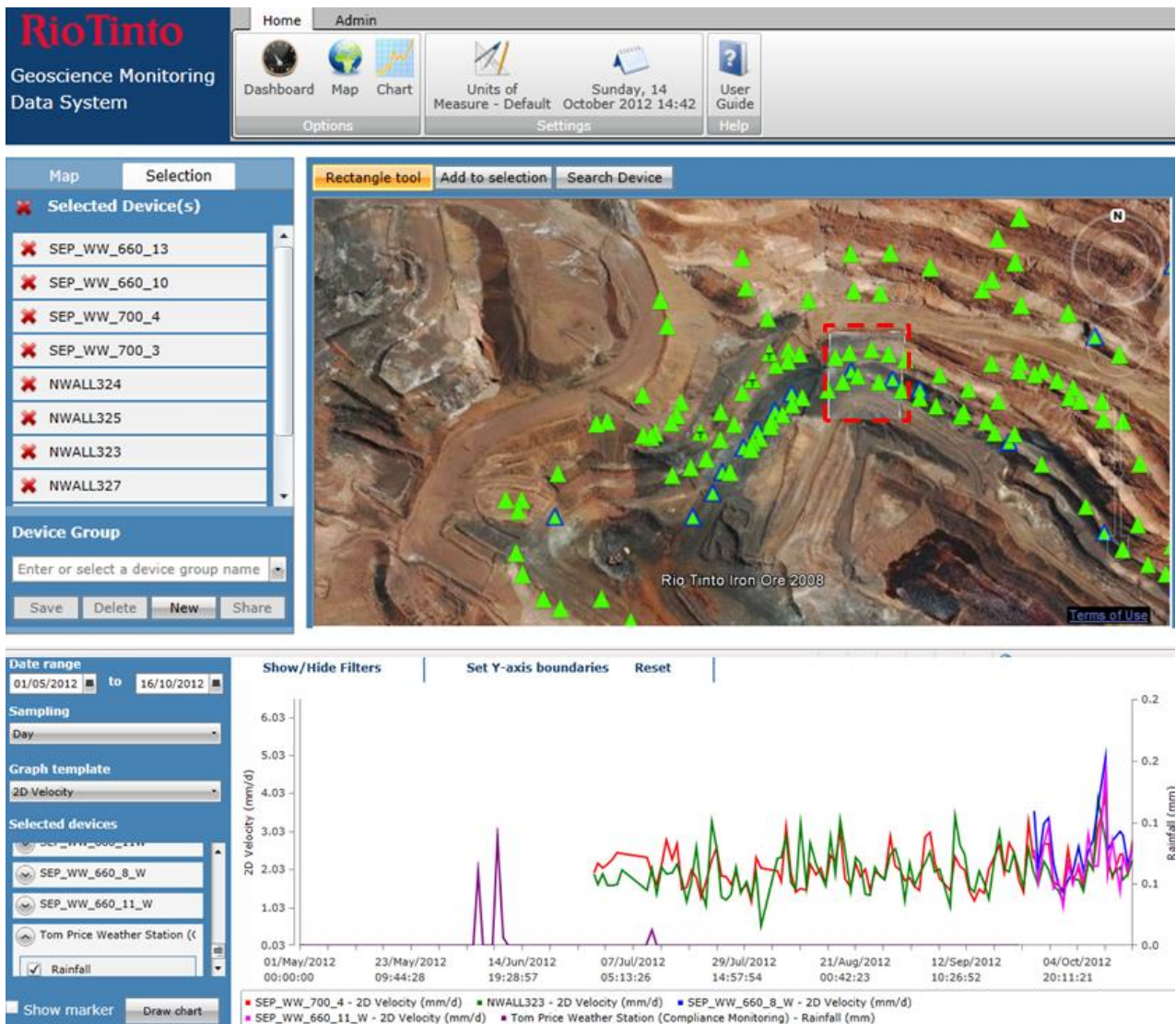
Figure 6 Example of prism monitoring data viewed in GMDS. Note the red rectangle which allowed the user to select a number of prisms visually on the image

Rio Tinto Iron Ore's integrated GMDS provides significant tangible benefits in the provision of:

- Summary dashboard showing system health and alarm status for key slope monitoring devices across Pilbara operations.

- Multi-pit coverage and technical support from a common focal point.

- Better identification of data gaps leading to improved monitoring coverage.

- Improved interpretation of monitoring data (spatial inter-dependencies, and correlations with other instrumentation types).

- Better utilisation of scarce technical resources (automation of labour intensive work).

- Standardised approach across operations (consistent reporting, analysis methods).

- Easy (permissions based) sharing of monitoring data, particularly for technical reviews, assistance or troubleshooting.

- Existing RTIO Google Maps and Google Earth Enterprise systems leveraged for expansion and rollout since terrain and imagery already exists.

Through these benefits, RTIO is able to lower the operational geotechnical risk profile by effectively improving slope monitoring practices. This tool provides the functionality to manage diverse instrumentation data in a consistent, standardised approach needed to support our geographically spread expansion plans.

10   Tablets and the future

GMDS provides a sound platform (as a desktop tool) for monitoring data review and improved understanding of spatial inter-relationships as well as visibility of alarm status and overall system health. Connectivity to other key data overlays (geology mapping, drillhole data, and current survey pick-up) provides a powerful array of data to improve slope performance understanding and support important engineering decisions.

Improved in-pit data network connectivity (to relay near real time data and model up-dates) and the use of microelectromechanical systems (accelerometer and gyroscope sensors) in tablets has presented exciting new frontiers in geotechnical data acquisition (monitoring and mapping), data and information presentation, field analysis and risk management. This has allowed the GMDS desktop application to be trialled as a near real time field tool on a tablet. This takes geoscience geo-referenced data availability to a new level. Using 3D gaming technology, different data types can be loaded onto the visual platform and support live, direct or indirect, view of a physical real-world environment whose elements are augmented by computer-generated input such as graphics or GPS data. For example, prism monitoring locations and current data responses can be observed and queried in-pit by aligning the tablet image with the actual slope and identifying the location of all prisms and other monitoring devices (Figure 7). Monitoring, structural and geological data can be dynamically compared with observed slope performance. The availability of geoscience data (monitoring, models, mapping etc.) and correlation with field conditions in real time, allows enhance understanding and judgement of slope performance.

Figure 7 In-pit augmented view on tablet

Important safety information can be made available in near real time. Geotechnical Hazard Alert areas are clearly identifiable and supporting information (mandatory controls, special access requirements) can all be accessed in pit prior to undertaking work. This essentially makes the Geotechnical Hazard Map (typically posted in crib rooms and offices) a live interactive feature available to all pit users. As with conventional geographical information systems, users are only limited by availability of georeferenced data types to combine, compare and contrast information. For example other spatial data can also be loaded onto this platform so that we can view:

- Geotechnical risk assessment sectors, fall of ground reports, and slope reconciliation sections.

- Mapped geological features.

- Zones of high and low grade.

- Zones of previous seepage.

- Areas of high potential for acid generation following dumping, etc.

This technology presents exciting live in-pit data interpretation and improved geotechnical risk management opportunities.

11   Conclusions

RTIO has utilised opportunities presented by the OC and GEE to expanded on existing monitoring systems and developed a geoscience monitoring data visualisation tool to assists with data and information analysis. The GMDS consolidates the Pilbara geoscience data into a single platform and provides transparency in monitoring system health and alarm status. It presents future opportunity to further develop the ability to access geoscience data in-pit, to allow enhanced slope perform monitoring and interpretation and geotechnical hazard management. This tool provides the functionality to manage diverse instrumentation data in a consistent, standardised approach needed to support our geographically spread expansion plans; and is in alignment with Rio Tinto's Mine of the Future and RTIO's Operations Centre vision by using technologies to reduce costs, increase efficiency and improve health, safety and environmental performance.

Acknowledgement

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