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Geohazard risk management for linear transportation

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Abstract

Railways that deliver ore from mines to market are critical to an operation's viability. Two examples of such railways include the Rio Tinto Iron Ore (RTIO) railway in the Pilbara region of Western Australia, and the Iron Ore Company of Canada (IOC) railway in northeastern Canada. Both railways are the only transportation mode from 17 mine sites to the ports to deliver their products to markets; annually, these railways ship over 330 million tonnes of iron ore (RTIO) and over 10 million tonnes of iron pellets (IOC). Although separated by over 16,000 km, different terrains, climates and operating regulations, these railways face similar challenges with respect to assessing and managing the risks associated with geohazards, in particular rockfall, landslides, and flooding geohazards. This paper presents risk-based frameworks for the IOC and RTIO railways, and the development of web and mobile based platforms to support effective geohazard risk-management practices within corporate risk frameworks. The output risk rating for each credible geohazard affecting the railway is used to support risk management through inspections, remediation projects and optimisation of maintenance and in situ or remote monitoring efforts. The geohazard management systems are also used in combination with live monitoring data to actively alert railway operators of changing conditions and potential triggering events, such as flooding or heavy rainfall. The systems that will be presented are used to support decision-making and communication of geohazard threats within their organisations.

Keywords: *geohazards, railway, risk-management systems, iron ore*

1 Introduction

Iron ore mines around the world face logistical challenges transporting ore from the mining property to ports for shipping and distribution. Railway lines are a commonly used mode of ore transportation as they can support the haulage of large volumes of material, frequently produced by iron ore mines. Two examples of such railways are the Rio Tinto Iron Ore (RTIO) railway in the Pilbara region of Western Australia and the Iron Ore Company of Canada (IOC) railway in northeastern Canada. Both railways represent the sole mode of transportation from mine to port. The RTIO railway annually transports over 330 million tonnes of iron ore, and the IOC railway transports over 10 million tonnes of iron ore pellets. These two railways are separated by over 16,000 km, operate in different terrain, climates, and operating regulations, however face similar challenges with respect to assessing and managing the risks associated with geohazards, in particular rockfall, landslides, and flooding geohazards.

In order to effectively manage geohazard and geotechnical assets along their railways, RTIO and IOC have embraced a holistic approach to geohazard risk management and are leveraging web-based geographic information systems (GIS) to support risk informed decision-making. This paper presents an overview of geohazard risk management along railways and the systems used by IOC and RTIO to actively prioritise sites for remediation and provide near-real-time warning to railway operators. Both IOC and RTIO utilise the Cambio^{TM} rail platform hosted by BGC Engineering. The systems are customised to accommodate the unique properties of both railways.

1.1 Geohazard risk-management philosophy

The fundamental idea behind geohazard risk-management is that all hazards and assets that can impact the normal operation of the railway are rated using a common framework that assesses the probability and severity of an adverse effect to health, property, or the environment. Risk is then estimated by the product of hazard probability of occurrence and consequences (Australian Geomechanics Society 2007). Geohazard risk assessments are used in several countries as a basis for development planning; for example. Austria, Switzerland, Australia, and Hong Kong. Examples of risk assessment approaches are presented by the Australian Geomechanics Society (2007); District of North Vancouver (2009); Hong Kong Geotechnical Engineering Office (1998); Porter et al. (2009); and Porter and Morgenstern (2013). An example geohazard risk assessment methodology is presented in Figure 1. This assessment is based on various internationally accepted methodologies (International Organization for Standardization 2009; Canadian Standards Association 1997).

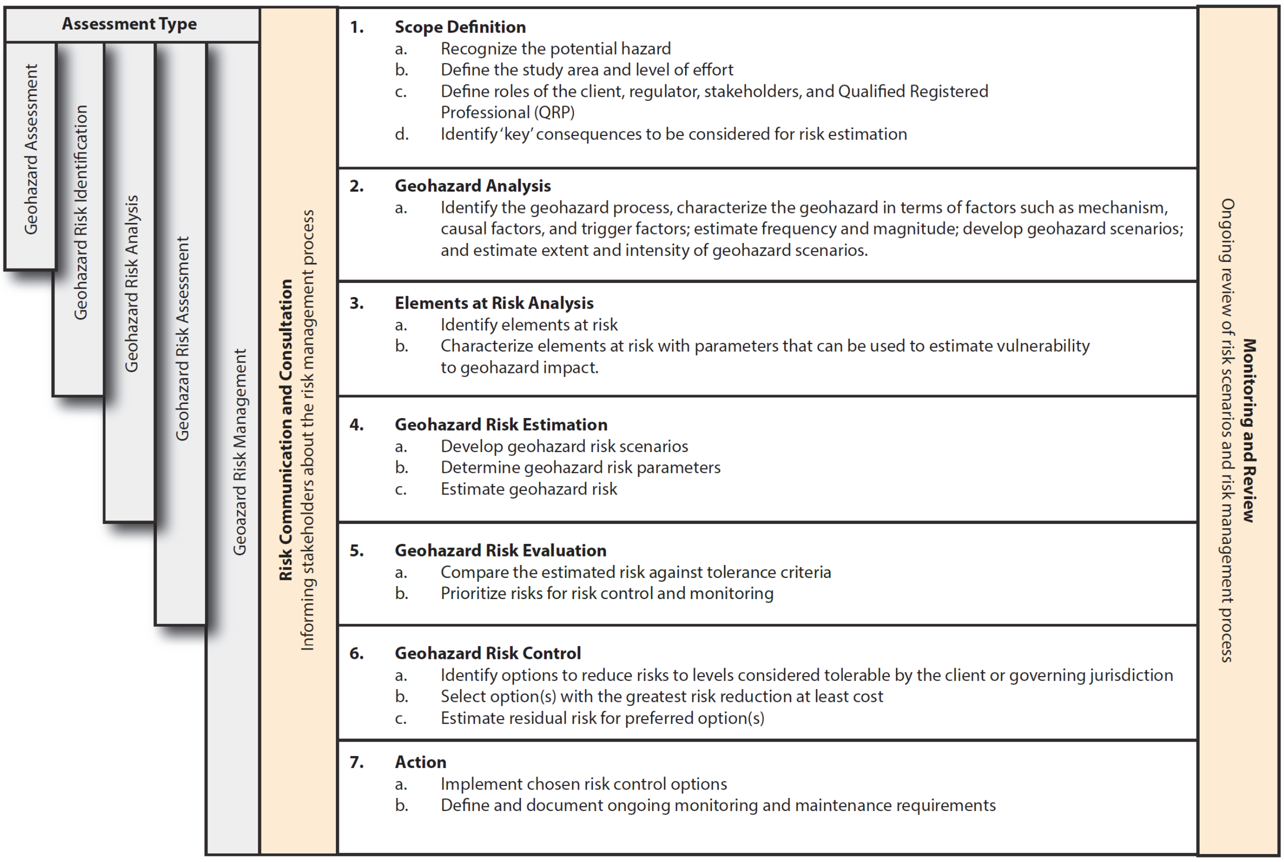

Figure 1 Generalised geohazard risk-management process (modified after International Organization for Standardization 2009; Canadian Standards Association 1997)

1.2 Project settings

The work presented in this paper occurred at two project sites; IOC in Northern Canada, and RTIO in Western Australia. The setting and background for each site is outlined in the following two sections.

1.2.1 Iron Ore Company of Canada

The IOC railway is located in northeastern Canada. The railway is approximately 400 km long connecting the mines in Labrador City, Newfoundland and Labrador to Sept Iles, Quebec (Figure 2). The railway was constructed between 1951 and 1954 between Sept Iles and Schefferville, Quebec, and extended in 1958 to connect with Labrador City. The railway is single track with multiple strategically located sidings to facilitate traffic in both directions. The railway is positioned adjacent to major rivers along the base of rugged slopes comprised predominantly of gneissic rocks of the Grenville province, and glacial till and outwash deposits comprised of sand, silt, and clay resulting from the Laurentide ice sheet that covered much of Canada. The IOC railway is exposed to four well-defined seasons with summer highs in the mid 20° Celsius (C) and winter lows in the mid -30°C, frequently dipping below -40°C.

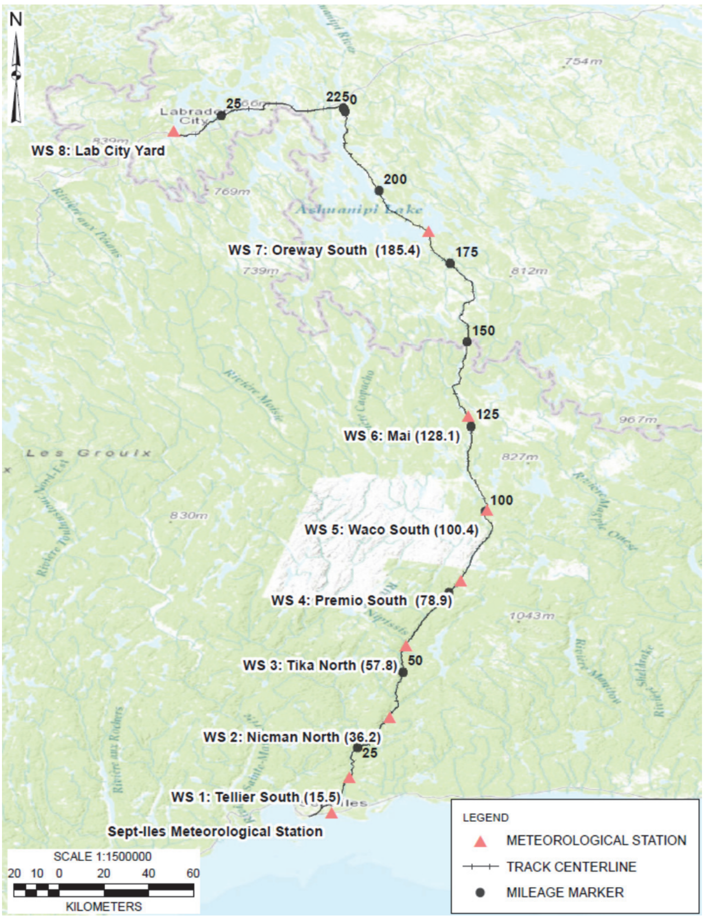

Figure 2 Map of the Iron Ore Company of Canada railway from Sept Iles, Quebec to Labrador City, Newfoundland and Labrador

The Cambio rail platform for IOC was developed and implemented in 2015, following a train derailment due to a landslide that resulted in the death of a locomotive engineer. The system is cloud-hosted on a website that provides relevant descriptive, quantitative and photographic information for each documented geohazard. The implementation of the system in 2015 and continued development over the past three years has led to a greater understanding of the potential risk from geohazards along the IOC railway.

The IOC geohazard-management approach estimates the relative risk of loss of life due to a train derailment resulting from a geohazard occurrence. The system considers five different geohazard types in a consistent framework facilitating the parallel evaluation of risk from the different geohazard types. The five geohazard types being considered are: rockfall, earth and debris landslide, bank erosion, washout, and avulsion. The risk rating level distinguishes the order of magnitude annual probability of loss of life from geohazards along the railway. The risk ratings are used to aid in the prioritisation of risk-management efforts, which include annual inspections, special inspections, and risk-control works.

1.2.2 Rio Tinto Iron Ore

The RTIO railway network is the largest privately owned and operated heavy haul rail system in Australia. The network consists of over 1,700 km of rail connecting 16 mine sites to four port terminals in the Pilbara region of Western Australia (Figure 3). Growing significantly since the first official iron ore train departed Tom Price operation on 16 July 1966, the network supported the delivery of 330.1 Mt of Pilbara iron ore shipments in 2017. With a continual focus on innovation to efficiently deliver production guidance, in September 2017, the first autonomous train without on-board human supervision was piloted on the mainline travelling nearly 100 km across the Pilbara. On schedule for full implementation by the end of 2018, AutoHaul® will be the world's first fully autonomous, heavy-haulage, long-distance rail system.

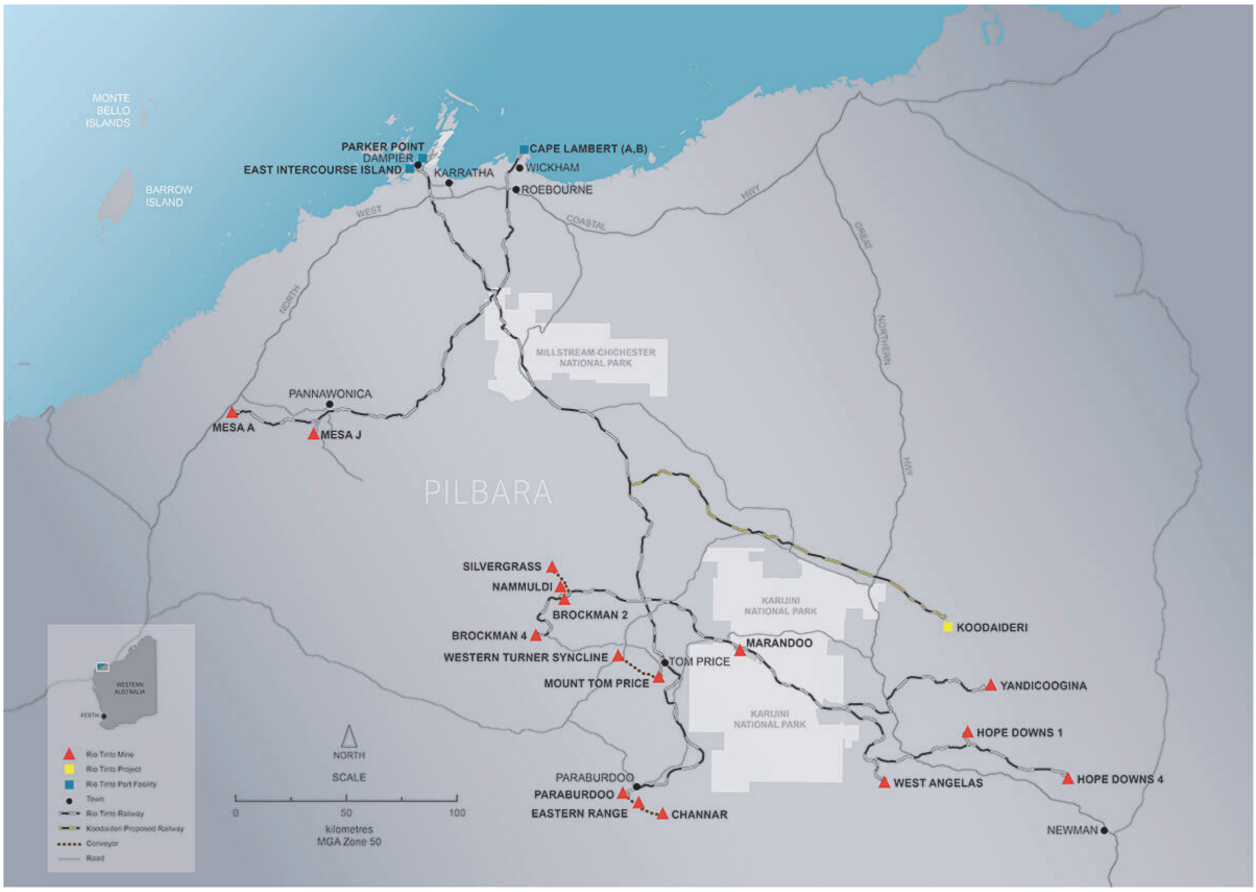

Figure 3 Rio Tinto Iron Ore Pilbara operations, Western Australia

In addition to the vast track infrastructure, immediately adjacent to the RTIO railway are slopes formed through both natural and man-made processes, and the railway has been divided into 1,208 individual cutting or fill segments. These sites range from less than 50 m to several kilometres in length (e.g. Figure 4), and require systems and processes to manage the risk associated with slope geohazards. Of the slope cutting sites, 80% are less than 10 m high, with the remaining 20% exceeding 10 m in height and are the specific focus for geohazard management. In addition to the slopes immediately adjacent to the railway, there are also extensive access roads providing maintenance access to the cuttings, embankments, over 3,000 culverts, and 55 bridge assets. The slopes adjacent to the RTIO railway are generally less extreme in height in comparison to IOC, yet the cumulative exposure across the rail network is significant.

Figure 4 Rio Tinto Iron Ore Pilbara operations

Historically, the primary means of monitoring of slopes, culverts and embankments is through visual inspection that generates detailed site-specific reports including condition and hazard observations, recommendations for ongoing risk management, and associated photographs. Each site will have multiple previous reports. However, there is limited visibility of the historical observations and recommendations as detail is lost in the thousands of individual reports. Future RTIO expansion projects, including Koodaideri, will significantly increase the number of slope, embankment and culvert assets further exasperating the data-management challenges in coming years.

The Pilbara region experiences average temperatures in excess of 33°C in the summer months. The annual rainfall is 300 to 400 mm, with a large portion of this occurring as high-intensity rainfall events in the cyclone period (October through April). With some areas of the mainline constructed over 50 years ago, when slope design and construction methods were not as sophisticated as today, deterioration of the slope condition has occurred under natural processes since construction. Limited maintenance works have historically been undertaken on the slopes themselves, other than routine drain clearing works. The assets continue to age, with many slopes requiring remedial maintenance works of varying degrees. Due to the large number of individual sites, it is critical to prioritise maintenance works and effectively allocate resources to the areas of higher risk first.

2 Geohazard risk concepts

The Rio Tinto D3 Management of Slope Geotechnical Hazards standard provides corporate guidance on the management of geotechnical hazards associated with natural slopes and slopes which are excavated in relation to mining activities or associated supporting infrastructure, including railways. The standard includes the requirement for the assessment of natural slope hazards, and slope-monitoring processes to ensure that geotechnical hazards have not increased significantly over time.

To effectively manage the risks and address the challenges presented by geohazards, and focus resources in the appropriate areas, the RTIO and IOC rail teams required a system where all aspects of geohazard management are captured in a single platform. A holistic approach, that aligns with current technological advances, to visualise geohazard risks and prioritise risk-management activities, with the ability to allocate work and resources appropriately for the extensive assets was required. Cambio provides this solution, to compile and transition all existing geotechnical risk-management information into a single web-based management system to support the D3 standard. Through early identification of geotechnical slope hazards, the associated risk can be evaluated, and a program of remedial works prioritised accordingly. By integrating a mobile application allowing infield data capture, improved inspection efficiency by civil and geotechnical inspectors for the vast number and spatially spread cutting, embankment, culvert, and bridge assets could also be realised.

Cambio extends across all components of risk management shown in Figure 1. However, this paper focuses primarily on the risk estimation component of risk management.

Risk estimation involves assessment of the likelihood that potentially damaging events will occur, affect elements at risk, and cause particular types and severities of consequences. Each of these three components of risk (event likelihood, elements at risk, consequences) is estimated separately and then combined to provide an estimate of the risk level. The objective is to provide a systematic, repeatable, and practical assessment of risk at an appropriate level of detail based on the information available and the intended use.

Risk estimation may be completed using qualitative, quantitative, or semi-quantitative methods. However, the governing formulation for all approaches uses the same concepts. A semi-quantitative risk-assessment framework is implemented for both the RTIO and IOC approaches, and evaluates the expected annual loss from train derailments resulting from geohazards, measured as a relative likelihood of loss.

The following sections describe how this general formulation for risk estimation is implemented in an operating railway environment. At its core, the system relies on expert judgement of H (hazard) and estimates of a few parameters to determine C (consequence), and thus to evaluate R (risk). The proposed approach is practical for application by qualified professionals assessing multiple geohazard types in a working railway environment.

3 Existing risk frameworks

3.1 Iron Ore Company of Canada risk formulation

The risk framework developed and implemented for the IOC railway considers the following for each geohazard along the railway:

1. The annual probability of impassable track at a specific location from the identified geohazard (i.e. the hazard, or H).
2. The probability of a fatal derailment given the presence of impassable track (i.e. the consequence, or C).
3. The risk (R), or the annual expected likelihood of loss of life from a geohazard-related derailment, determined as a combination of hazard and consequence (H × C).

The general formulation of risk estimation, adapted for a single geohazard scenario of a train encountering impassable track, is hereby defined as:

$$\text{Risk (R)} = \text{Hazard (H)} \times \text{Consequence (C)} \tag{1}$$

$$R = (P_{gh} \times L_{it}) \times (L_d \times V \times E) \tag{2}$$

where:

- R = Risk. The expected loss, in this case the annual expected likelihood of loss of life from a geohazard-related derailment due to a geohazard event at a specific location along the IOC railway.
- H = Hazard. The annual probability of track being impassable to rail traffic from a geohazard.
- C = Consequence. Probability of a derailment resulting in fatality given the presence of impassable track.
- P_{gh} = Geohazard probability. Annual probability that a geohazard will initiate at a specific location and reach its zone of influence on the infrastructure (e.g. track, embankment). This term includes both the annual frequency of occurrence and the spatial component of the event reaching its zone of influence.
- L_{it} = Likelihood of impassable track. Likelihood that the given geohazard with a specific magnitude reaching the zone of influence will make the track impassable to a train at normal track operating speed.
- L_d = Likelihood of derailment. Likelihood a train will encounter the impassable track condition and derail.
- V = Vulnerability. Vulnerability of the element at risk (e.g. train crew in the locomotive) to loss, defined as the likelihood that elements at risk will suffer defined consequences (e.g. at least one fatality) given the derailment of a train.
- E = Elements at risk. A measure of the value of the element at risk. In this case, E = the number of persons exposed to loss of life in the event of a derailment. The typical case assumes one train worker on IOC trains.

This formulation provides an approach that allows all geohazards that have the ability to cause a train derailment by making the track impassable to be rated in a consistent manner which allows for simplified communication of risk and management strategies.

3.2 Rio Tinto Iron Ore slope risk matrix

In 2017, RTIO developed a detailed risk assessment framework for evaluating cutting and embankment slopes along the railway. The rail slope risk matrix was developed primarily to compare risks across the system to support prioritisation of slope monitoring and remedial maintenance works. Given the number of individual sites, it was important that the risk assessment considered factors already captured through existing visual inspections and that the process was automated. The risk level is assessed for three different scenarios at each location; two evaluating personal safety impact and one economic impact. The scenarios are:

- Rockfall injuring person: A person is present at the toe of the slope and slope failure occurs, injuring the person. This scenario considers the risk to rail maintenance teams responsible for visual inspections and on-track maintenance works on foot.
- Derailment injuring a train driver: Derailment occurs as a result of material on the track, or of a loss of formation support, and injures the driver.
- Material on track impacts production: Material falls on the track, or formation support is lost due to embankment instability, and requires removal from the track, leading to a service disruption and impact to production volumes.

The assessment method is aligned with the Rio Tinto risk framework where risk is the combination of likelihood and consequence. The inherent risk is assessed (i.e. without any monitoring or remedial controls implemented).

3.2.1 Scenario 1: rockfall injuring a person

Scenario 1 considers the risk associated with rockfall injuring a person who is performing track maintenance or inspections on foot. The likelihood of instability, and the potential consequence based on the slope geometry are considered (Figure 5 and Table 1).

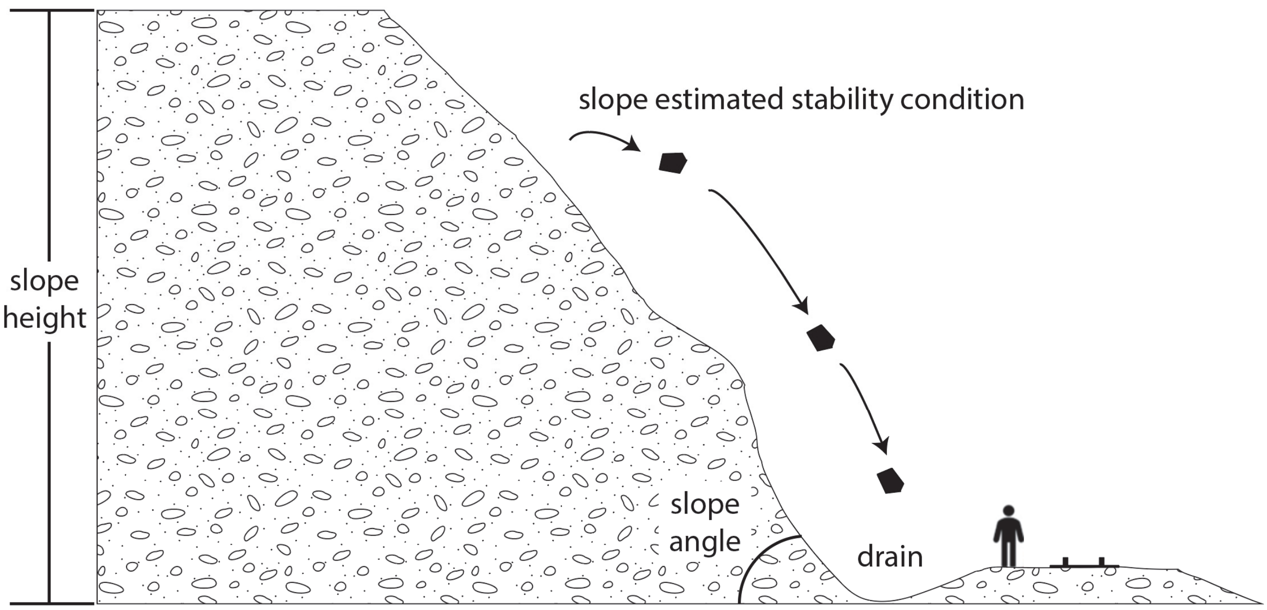

Figure 5 Conceptual illustration of cutting failure case for scenario 1, rockfall injuring a person

The likelihood of instability is the probability of slope failure and/or rockfall, based on direct observation of instability during the inspection, as described in Table 1.

Table 1 Likelihood of slope instability

Category	Description
Almost certain	Active instability observed, likely to extend in future
Likely	Active instability observed
Possible	Obvious signs of some movement, expect some ongoing movement
Unlikely	Minimal instability observed
Rare	No instability observed

The consequence considers the slope geometry which is a combination of slope height and slope angle (Table 2). The consequence categories pertain to specific definitions within the Rio Tinto corporate risk framework. Distance from track and drain geometry were not included since a person might be working close to the face. During the development of the consequence matrix, other slope risk classification methods were consulted including the RTA Guide to Slope Risk Analysis, prepared for the Roads and Traffic Authority of New South Wales (RTA) (Stewart et al. 2002). The document provides a process for assessing geotechnical risks of slopes adjacent to main roads in New South Wales. Whilst some of these concepts were taken into consideration, namely aspects of the slope description and geometry classifications, the risk exposure elements were deemed to be too different to implement. The RTA guideline includes a rockfall simulation which found that roll distances peaked for slopes ranging between 60° and 70°. This was included as the worst case in the consequence matrix (Table 2). Sense-checking of the consequence outcomes from the RTIO matrix was also completed via field checks and review of existing inspection reports, to ensure that the developed classification was fit for purpose.

Table 2 Consequence of slope instability

Slope angle	Slope height				
	≤5 m	6 ≤ 10 m	11 ≤ 15 m	16 ≤ 20 m	>20 m
<40°	Minor	Minor	Minor	Minor	Medium
40–50°	Minor	Minor	Medium	Medium	Serious
>70°	Minor	Medium	Medium	Serious	Major
50–60°	Minor	Medium	Serious	Major	Major
60–70°	Minor	Medium	Major	Major	Major

3.2.2 Scenarios 2 and 3: derailment Injuring driver and material on track impacts production

Both scenarios 2 and 3 consider where the track is impassable due to a failed volume of slope blocking the track (Figure 6). Factors that are considered in these scenarios include:

- Drain capacity: drain catchment volume, estimated from drain measurements.
- Material on track: to estimate the material reporting to the track, the drain capacity is subtracted from the potential failed volume.
- Daily production: expected haulage (k t/day), for the applicable track section. Note that haulage tonnages vary along the network due to the various mine operations sources.
- Impact duration: expected duration of a service outage (days), considering the expected volume of material on the track.
- Access to the hazard zone: factor applied depending on how readily accessible the area is for works to remediate the failed volume and slope, and minimise further impacts to production. Range considered: good access, some access or poor access.
- Number of tracks: factor applied depending on whether the affected section is single or dual track.

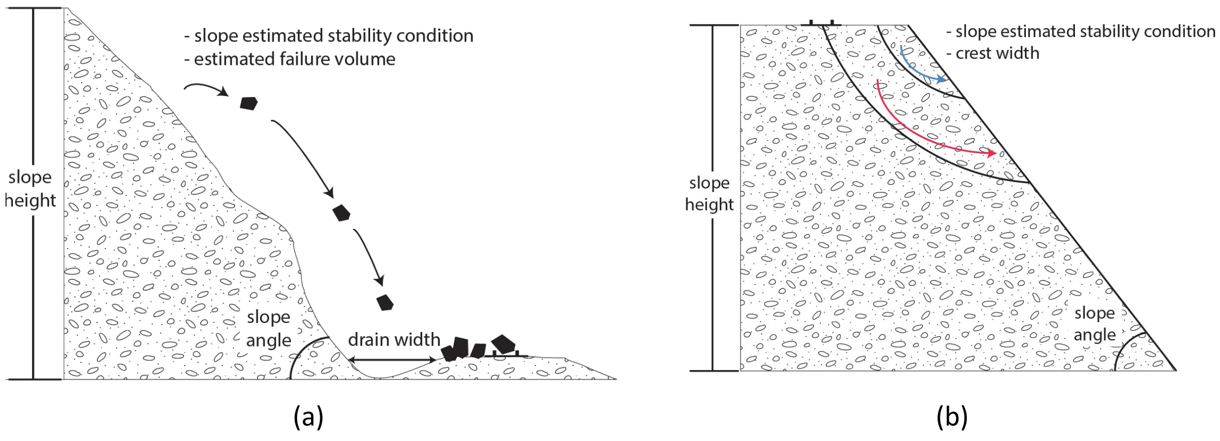

Figure 6 Conceptual illustrations of slope failure case for scenarios 2 and 3 for (a) cuttings and (b) embankments

Once each scenario has been assessed and the risk level determined, a priority is assigned for the site which considers the risk level for all scenarios. A slope with higher risk ratings for all three scenarios will have a greater priority than for a slope with higher risk ratings for only one or two scenarios. The priority determines the sequence for remedial slope maintenance and ensures that areas of higher risk are addressed ahead of lower risk areas. Slope monitoring and control requirements, through targeted visual inspections or other controls such as rockfall fencing, are also planned based on the outcomes of the risk assessment. Following development of the slope risk matrix, BGC Engineering was engaged to review the existing methodology and provide external review and recommendations on the suitability of the methodology. Minor re-tooling enhancements to existing algorithms will be considered during the transition to Cambio.

4 Geohazard risk-management systems

Cambio is a cloud-hosted web accessible system that provides a searchable repository of data and information from preliminary desktop to detailed field and construction reporting. It allows users to store data in a single database directly referenced to the spatial location and time the data were collected. The information stored is customised to suit the requirements of the operator.

The data and information in Cambio supports the screening, monitoring, assessment and management of geohazard risks. The data are gathered via fieldwork, automated real-time instrumentation, and weather and satellite data. An example dashboard used by IOC is presented in Figure 7.

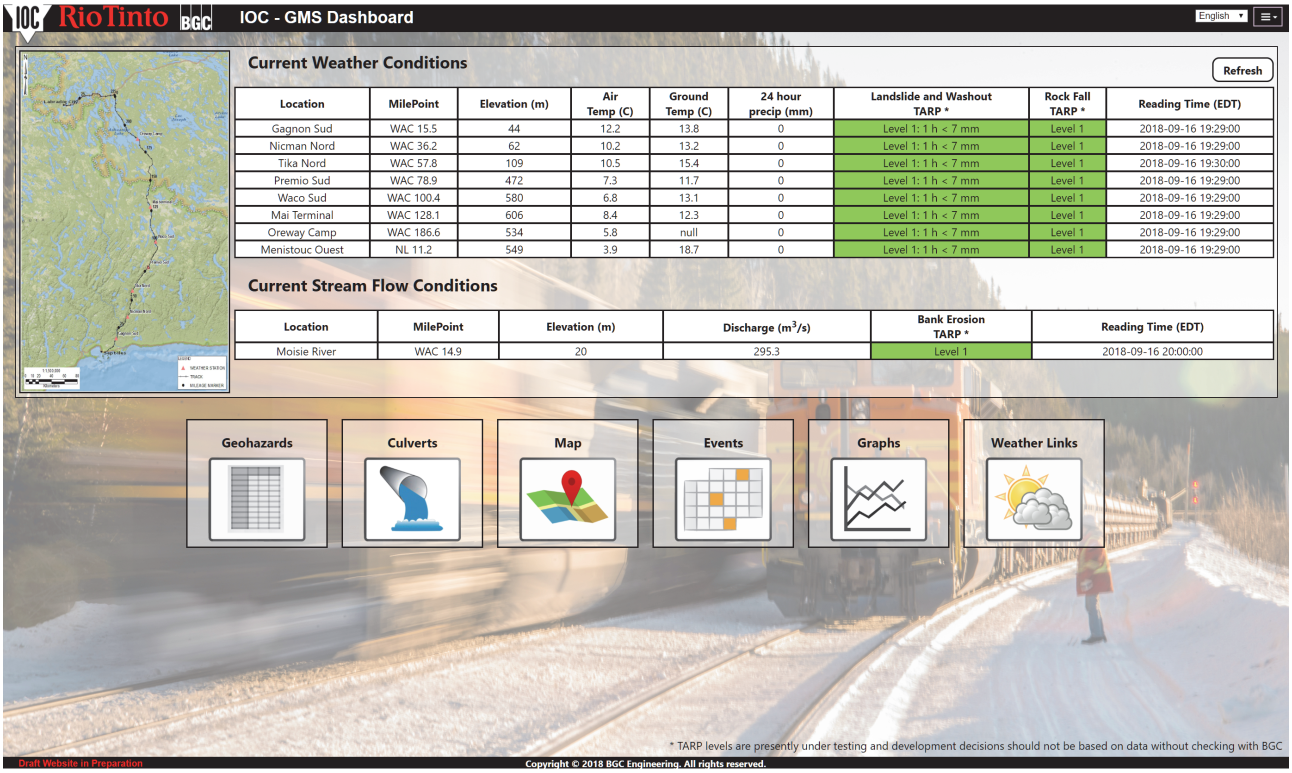

Figure 7 Example Cambio web interface dashboard to maps, instrumentation, geohazard rating, and present warning levels across the rail network

Utilising mobile field applications, engineers and operators can take information stored in Cambio to site and allows information to be entered in the field. This facilitates a stronger connection between site work, inspections, and reporting. An example site inspection is presented in Figure 8 where information is broken down by level of detail from site information and hazard type, through to rating summary and rating details.

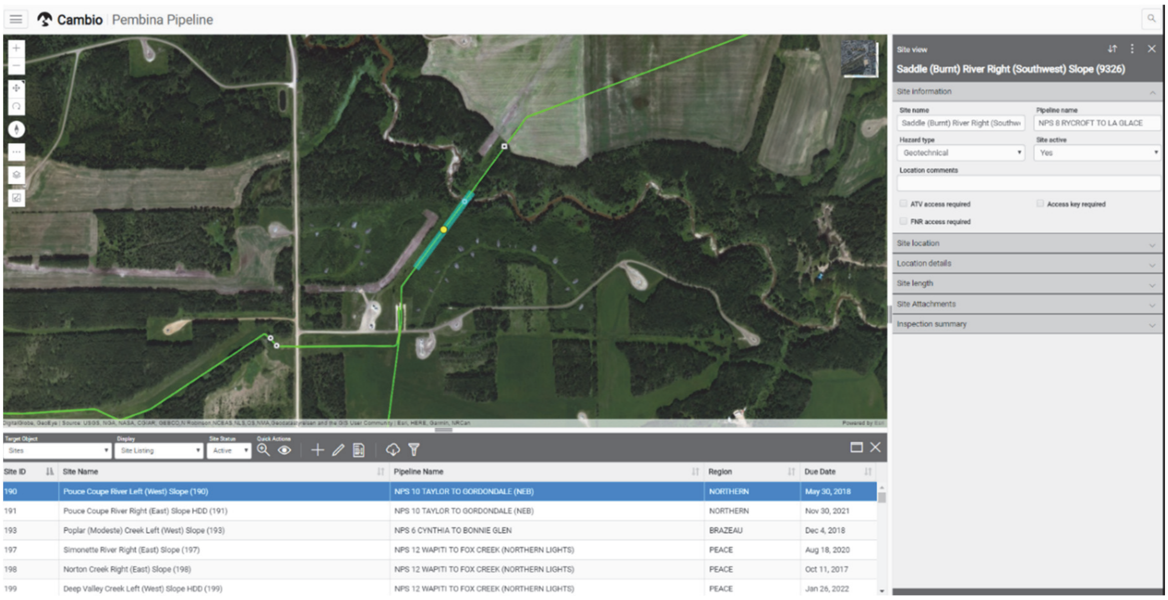

Figure 8 Example Cambio web interface illustrating site details and information easily accessible to the user

5 Challenges

Development and implementation of the Cambio system for IOC had many challenges that required creative thinking to accommodate. During the operation of the system over the past three years, adjustments have been made based on user feedback and unforeseen operational limitations. Some of the current challenges we face today that remain a point of tension include:

- The number of judgement based decisions which support the risk ratings can be challenging to compare between sites. Recent work presented by Whittall et al. (2019) advances this concept.
- The system at present does not account for the spatial extent of geohazard sites, and how that factors into the hazard (and risk) ratings. For example, a 1 km long section affected by debris slides likely is much worse than a 100 m long section with the same characteristics, and the current formulation can struggle with this differentiation.
- The current landslide trigger action response plans are not weighted based on risk, which can lead to operational challenges during elevated warning periods.
- The present system focuses solely on loss of life as the consequence. Incorporating service outage alongside derailment that result in fatality as the governing consequence could add robustness to the system.

As part of the initial scoping for the RTIO rail geohazard management system, it was identified that existing applications were in use for managing different aspects of slope management. However, there was not one package that could readily incorporate all elements to allow for informed decisions on slope management to be made. For example, viewing of maps can be achieved in ArcGIS. However, this cannot handle inspection and maintenance planning and management. RAMSYS is currently used for railway infrastructure assets related to track, operational information (i.e. speeds), various condition data, and in particular, measurement data coming from different measuring systems (i.e. track geometry, rail profile, and rail corrugation). RAMSYS has not been customised to collate geohazard monitoring data and risk assessment or manage inspections for slopes (cuttings and embankments) or culverts. Visual inspection and remediation planning and tracking are currently completed in SAP, and report attachments can be added to notifications. However, the system does not have the ability to link all historical inspections, photographs, risk assessment, and map functions. A potential barrier to the success of implementing Cambio will be the linkages to these data sources and ensuring that there is no duplication of data entry. The advantages for the end user if all, or as many as possible, of these components can be aggregated into one platform, is obvious.

6 Opportunities

The development of Cambio is advanced, yet remains in its infancy. The future vision will allow for the integration of satellite data and information, weather forecasts, groundwater, and connected devices that will leverage artificial intelligence to facilitate better decisions, faster, and more accurately. Cambio will be integrated with three-dimensional (3D) visualisation methods such as augmented and mixed reality to allow owners and operators to view their sites in true 3D and interact with data in real time. A significant opportunity will be through the integration with SAP to allow maintenance orders to be issued from Cambio, further reducing the gap between efficient maintenance and operation with geohazard risk management.

6.1 Mobile application

Multiple levels of inspection are completed for cuttings, embankment, culvert, and bridge assets. As described in Section 3.2, the RTIO slope risk matrix requires inputs from visual inspections to update the risk level. Current practice is for civil and geotechnical specialists to complete two different levels of field inspections, record hand-notes and take photographs of their observations at each location. Upon return to the office, a report is prepared and field data is entered into a separate spreadsheet to allow RTIO to update the slope risk matrix. This is not an efficient process due to double handling of the observational data collected. The proposed Cambio system will link the inspection information to the risk update through standard reporting templates available in the field via a mobile application. The risk will be automatically updated for each location, with photos and observations captured linked in the system. This will provide improved efficiency for inspectors of civil assets. Via the mobile application, previous reports will be available for inspectors to compare observations with previous assessments at the site. An electronic system will also make historical inspection records more accessible and easy to find.

6.2 Expansion to other areas in Rio Tinto Iron Ore

RTIO have identified other areas of the business, external to the railway, where geohazard management and specifically slope management could potentially be incorporated into Cambio. The areas being considered include the:

- Extensive mine access operations access roads.
- Management of utilities including power, water and fuel linear infrastructure.
- Natural and man-made slopes and stockpiles at the Cape Lambert and Dampier Port facilities.
- Significant natural slopes surrounding the construction of drilling pads and access tracks to these areas. Approximately 10,000 drilling sites are prepared each year in Western Australia.

7 Conclusion

Cambio is a risk-based geohazard management system fundamentally based on an inventory of potential geohazards, each of which are evaluated for risk with respect to consequences pertinent to the operation. It provides a searchable repository of data and information from preliminary desktop to detailed field and construction reporting. It allows users to store data in a single database directly referenced to the spatial location and time the data were collected.

A key strength of Cambio is through leveraging the methodical structure, the user is able to go back to the quantitative roots of the framework and generate pseudo-quantitative risk values that can be used for ranking and for estimating potential for loss avoidance through mitigation. This is a powerful tool to communicate the benefits of risk management, and the opportunity to improve performance through investment in risk reduction.

RTIO and IOC represent operations that vary in spatial extent, hazard level, operating environment and service requirements. However, using the framework of data organisation within Cambio and the ability to systematically turn data into knowledge for communication and decision-making allows both operations to utilise the system.

Cambio is accessed through a web application that supports the screening, monitoring, assessment and management of geotechnical data and information. The system supports data collected in the field, automated real-time instrumentation, and weather and satellite data. The information generated supports proactive management and planning for inspections and allocating resources at the appropriate level based on the significance of the risk. Geotechnical management decisions become more cost-effective, defensible, better documented, transparent, and easily communicated to regulators and senior management.

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