GEOTECHNICAL RISK / PROJECT MANAGEMENT FOR HEAVY HAUL RAIL DEVELOPMENT OVER KARST TERRAIN IN THE PILBARA

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SUMMARY
Rio Tinto's 1600km iron ore rail network in the Pilbara is the largest privately owned railway in the world. Whilst train lengths are up to 2.4km, axle loads 36 tonnes and loaded speeds 70km/h; the harsh terrain, ground conditions and associated geo-hazards potentially create the most significant engineering challenge for development, operation and maintenance of this major asset.

Geotechnical risk management was incorporated into overall project management for delivery of the 54km, Hope Downs 4 rail project over karst terrain where cavities up to 10m wide were encountered within 2m of the rail formation. The process included early development and continuous updating of the ground model and risk register, ensuring engineering solutions were designed and integrated into the wider project delivery schedules and budget.

Two phases of geophysics and a detailed drilling programme gave a unique opportunity to 'test' the ground model and review the benefits and limitations of the various methods used to manage/mitigate karst terrain risks. A suggested karst risk management procedure for future rail projects is presented.

1. INTRODUCTION
Rio Tinto's iron ore rail network in the Pilbara, Western Australia currently supports 15 mines with a combined annual production of 290 million tonnes. Future developments will optimise the existing asset and link additional ore bodies to the 3 port facilities at Dampier (Parker Point and East Intercourse Island) and Cape Lambert.

The total rail network length is 1600km and the straight line distance between the northern and southern extents at Cape Lambert and West Angelas respectively is 325km. Put into context to show the scale of operations, this is around the same distance as travelling from Sydney to Canberra or from London to Paris. A schematic map of the network is provided in Figure 1.

To support such productivity, 2.4km long trains weighing just over 30,000 tonnes haul iron ore to the ports at main line loaded speeds up to 70km/h.

![Figure 1: Schematic of Rio Tinto's privately owned iron ore rail network](image-url)
development, operation and maintenance of this major asset.

Identifying geo-hazards and managing the geotechnical risks that result e.g. settlement or ground collapse into underlying cavities in karst terrain, requires implementation of a robust and systematic geotechnical risk management strategy commencing at the earliest opportunity in the project. Of even greater importance, the geotechnical risk management strategy should be integrated into the broader project management drivers and objectives. Arguably, not doing so introduces the greatest geotechnical risk of all to the project.

2. GEOTECHNICAL RISK & PROJECT MANAGEMENT

Ground related problems can have a significant impact on the delivery of rail projects. Often, they are compounded because groundworks / earthworks e.g. rail embankments, cuttings and geo-material management are completed very early in a project (or separable package) and problems affect all later stages. For example, they can affect; track laying, signalling and commissioning (cost and schedule), profitability, health & safety, quality, fitness for purpose, rail operations and the environment.

Some of the key reasons why ground related risks are so significant to rail projects include:

- The nature and distribution of ground, groundwater and resultant geo-materials are the result of dynamic, natural processes over geological time (millions if not billions of years). Their characteristics are therefore un-determined and can vary considerably over short distances and depth.

- By contrast, other construction materials such as steel rails and concrete sleepers are manufactured and their characteristics are well controlled to meet pre-determined specifications.

Calyton [1] defined geotechnical risk as, ‘the risk to building and construction work created by the site ground conditions’. Significantly, his publication further explores causes of geotechnical risks and concludes that they are created by both the inherent ground conditions and the geo-engineering process. This opinion is substantiated by authors such as McMahon [2], Trenter [3] and Baynes [4]. Ultimately, this means that geotechnical risks are as much associated with how projects are engineered, managed and constructed by the project team, as they are with the inherent ground conditions.

Subsequently, geotechnical risks can be considered in terms of three key components:

- Design or technical risk which includes uncertainty due to site geology (geological / ground model), appropriateness of the engineering analyses undertaken and reliability of the engineering properties assigned to the ground.

- Contractual risk or transfer of risk through the contract.

- Project management risk since project managers have ultimate ownership of project delivery and all risk management.

An idealised geotechnical risk management framework to be incorporated into overall project management was proposed in [1]. It forms the basis of Figure 2, although the figure has been simplified and adapted to reflect the overarching principles used to successfully manage karst risk on the Hope Downs 4 rail project described herein.

3. KARST TERRAIN

The subject of karst terrain development and associated landforms has been very well documented in the literature. Some of the most informative works include Dearman [5], Waltham & Fookes [6], Bell, Culshaw & Waltham [7] and Waltham [8]. A brief outline is provided here to give a general understanding of associated risks in the context of rail development in the Pilbara.

Karst terrain is characterised by surface and sub-surface features caused by dissolving of soluble, carbonate rocks such as limestone, dolomite and calcrete. Karst features include sinkholes, cavities, springs, disappearing streams, enlarged rock joints / bedding planes and pinnacle zones. They are not always observable at the ground surface making karst terrain particularly difficult to predict, investigate and build railways across.

The rate of dissolving is very slow and exposed rock surfaces retreat no more than a few mm per 100 years. Consequently, the most significant geo-hazard from karst terrain is ground collapse into pre-existing cavities (sinkholes). Subsidence sinkholes, where overlying soil is washed down into cavities are the most common cause of ground failure.

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Sudden collapse can occur if the overlying soil has some temporary capacity to 'bridge' the cavity. A schematic section of a subsidence sinkhole is provided in Figure 3, modified from an example in [8].

Figure 3: Formation of subsidence sinkholes after [8].

Sinkholes rarely occur in areas of undisturbed ground and the vast majority are induced by ground disturbance, most notably engineering activity such as increased water infiltration or lowering of the groundwater table [8].

Collapse of overlying roof rock into cavities is also rare. However, where significant additional loads are applied to the cavity roof, e.g. from new rail lines, sudden collapse is possible, particularly where roof cover is thin or the rock mass is of poor quality.

4. HOPE DOWNS 4 RAIL PROJECT

4.1 Introduction

The 54km, Hope Downs 4 rail project was designed and constructed between mid 2011 and mid 2013. It established a rail link between the existing Lang Hancock Railway and the Hope Downs 4 ore body (see Figure 1 for approximate location).

4.2 Project Planning Stage - Geo-hazard Identification

Karst terrain and associated cavities in calcium carbonate rich materials were identified as a key geotechnical risk at project planning stage and were included in the overarching project risk register. This was based on a high level review of the Pilbara’s geological history and the likely rock types to be encountered along the proposed rail alignment.

The Pilbara is a cratonic area i.e. a very old and stable part of the earth's crust. It has underlying igneous and metamorphic Basement rocks (3 billion years old) that are overlain in the south by younger (2.5 billion
years old) volcanics and sediments. The sediments include banded iron formations (iron ore), sandstones, mudstones and dolomite – a carbonate rock prone to the development of karst terrain.

Since formation of these earliest rocks, the Pilbara has been sculpted and modified by many natural processes including tectonics, weathering, erosion and deposition. In the recent geological past, such processes re-worked the soil and rock to form superficial deposits. Included are hardened duricrusts formed by the growth of minerals in near surface horizons. Where the cementing agent is calcium carbonate, karst prone calcrite is formed.

Figure 4 shows the general distribution of calcium carbonate rich materials in the Pilbara, with the Hope Downs 4 project and other rail networks superimposed. As can be seen, they are widespread with the potential to affect many of the existing and proposed rail lines.

![Diagram of Pilbara rail network and geological features](image)

**Figure 4**: Approximate areas of the Pilbara with potential for dolomite, calcrite and other carbonates (and hence karst terrain).

4.3 Concept Design - Desk Study and Engineering Geological Mapping

4.3.1 Desk Study

Geotechnical and specifically karst risk management continued in the concept design phase via a study of readily available information sources. These included; plans of the proposed rail corridor, published geological maps, aerial photographs, topographic maps, Lidar survey data, hydrological plans (showing drainage patterns), geotechnical investigations previously undertaken in the area by Rio Tinto, anecdotal information from experienced construction staff who had worked on previous projects, academic literature and published books.

The desk study further refined the likely extent of dolomite for approximately 5.4km at the western end of the rail alignment. It also confirmed the presence of calcrite for an approximately 7.5km section in and around the rail loop at the eastern extent of the project.

The desk study findings were presented to the project manager and wider project team via engineering geological maps and design tables that sub-divide the alignment into sections or domains with similar engineering characteristics. Their primary function is to make communication of geo-hazards and associated risks systematic and easy to incorporate into design, planning, construction and operation of the railway. Domains form the basis of the conceptual ground model and risk register and all information from later stages of geotechnical risk management are incorporated i.e. they are continually updated as new information becomes available.

Figure 5 shows an example, simplified engineering geological map and design table (risk register) for the Calcrete Domain located around the Hope Downs 4 rail loop. For convenience, and to demonstrate their use, this simplified version concentrates only on karst risks. It also shows additional information including mapped sinkholes that were incorporated in subsequent phases of investigation as the model was updated.

4.3.2 Engineering Geological Mapping

With areas of potential karst risk now better delineated, field mapping was completed. As the next phase of risk management, its key objectives were to further define the extent of dolomite and calcrite and to inspect for evidence of existing sinkholes or other karst related features. Mapping is a cost effective, non intrusive and fast way of further understanding the inherent ground conditions and ensuring future, more expensive investigation techniques such as geophysics, proof drilling etc. are targeted and only used where needed.
Dolomite interbedded with shale was observed in the Dolomite Domain. The underlying ground model was interpreted as a geological fold, which had been tilted eastward and subsequently eroded to expose the karst prone dolomite in the valley centre. Sinkholes were observed in several locations beneath, and close to the proposed rail alignment.

Figure 5: Simplified engineering geological map and design table (ground model and risk register) for the Calcrete Domain

Mapping the frequency of existing sinkholes and other karst features has been used on projects worldwide to develop a statistical likelihood that future sinkholes could occur, see Baynes et al [9]. If a low frequency is proven, a project management decision could potentially be made to accept the resulting risk and undertake no further karst risk management. The simplified engineering geological map for the Calcrete Domain on the Hope Downs 4 project (Figure 5) shows in excess of 20 existing and observable karst related features within 750m of the proposed rail alignment. Therefore, it was considered inappropriate to simply accept the prevailing risk of future sinkhole development and further karst risk management was planned and implemented during ongoing phases of the project.

Figure 6: Example, existing sinkhole

In the Calcrete Domain, variably cemented calcrete formed low rounded hills with well-developed drainage channels. A number of sinkholes (Figure 6) and several 1-2m wide cavities in the banks of creek beds (Figure 7) were observed. Other karst features such as slot gullies and tunnel gullies (sometimes collapsed) were noted. They were up to 5m wide.
As an example, it was deemed more appropriate, based on cost and schedule implications, to include proof drilling of karst anomalies in the construction phase of the project. Suitable drilling equipment needed for drill and blast operations was scheduled to be on site during much of the construction phase in the Dolomite and Calcrete Domains. Making use of this resource would reduce the cost of proof drilling works (the most expensive of all the investigation techniques) and the work would be completed when the project was a fully established construction site with all the Health & Safety and Site Management benefits that result.

4.4 Geophysical Explorations

As described in McDowell et al [10], geophysical explorations provide an indirect approach for investigating ground conditions. They measure various physical properties such as shear wave velocities, electrical conductivity and resistivity. Interpreting the results must be accompanied by other direct / intrusive investigation methods such as test pits and boreholes. Consequently, and perhaps contrary to some belief, they are a geotechnical risk management tool to be used as part of the overarching framework and only in conjunction with other techniques.

Discussing the various geophysical investigation techniques is beyond the scope of this document. However, all have unique benefits and limitations, and advice from a specialist geophysicist is always required. [10] provides guidance on the relative effectiveness of various methods and Figure 8 shows those best suited to detecting cavities. Unlike most engineering applications described in the research e.g. depth to bedrock, no techniques for cavity detection have the highest available rating of 4.

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geophysicist, Ground Probing Radar was selected. A notable limitation, as advised by the specialist, is a maximum investigation depth of around 7m. This was shallower than the base of some rail cuttings in the Calcrete Domain and it was recognised that further stage(s) of GPR and other investigation techniques would be required after their excavation. Again, given the systematic approach and ongoing reviews with the project manager, these could be readily factored into ongoing project planning and the overarching construction schedule.

4.4.2 Test Pits

Anomalies were identified in GPR surveys for both the Dolomite and Calcrete Domains. Given the likely limitations described in Section 4.4.1, anomalies were deemed higher risk areas requiring further and targeted evaluation, rather than where karst generated cavities would definitely be encountered.

Test pits were undertaken in areas that were accessible during the design phases. Despite their simplicity compared to other methods, they have many significant applications in all geotechnical investigations, and specifically in karst terrain. Most notably for the Hope Downs 4 project these were:

- Assessment of excavatability which can change rapidly over short depths and distances in karst terrain e.g. where rock pinnacles are located directly adjacent to karst features filled with younger sediments.
- Soil and rock sampling for laboratory testing to determine physical and chemical properties. This can include calcium carbonate content and hence relative susceptibility to development of karst terrain if required.
- Confirming the depths and extents of particular material types including the maximum depth of karst prone material where sufficiently shallow.
- The ability to actually observe near surface ground conditions, including karst features (Figure 9), and determine whether they are filled with sediments, open cavities and whether water still flows through them.
- Inspecting areas where shallow geophysical anomalies had been identified giving direct feedback on the effectiveness of the geophysical technique used in that particular ground type.

![Figure 9: Example karst feature exposed during a test pit inspection of a suspected karst anomaly.](image)

5. CONSTRUCTION PHASE

It is important to note that going into the construction phase, all voids associated with karst terrain along the rail alignment were not, and could not realistically have been identified. Instead, previous phases of geotechnical risk management had progressively refined areas of their likely occurrence and form.

Consequently, designing specific remedial measures, producing definitive Scopes of Work and Specifications as well as producing precise cost and schedule implications was unrealistic. This is particularly the case for rail projects where considerable lengths of the alignment can potentially be exposed to the karst risk.

Therefore, and in line with the geotechnical risk management framework, a systematic approach was also adopted through construction.

5.1 Review of Viable Karst Remediation Methods

In conjunction with project management, methods most likely suited to remediating karst features on the project had been reviewed during detailed design. The review took into consideration; constructability (safety), likely nature of the karst features to be remediated, technical robustness, simplicity, other site activities likely to take place at the same time, material availability and the experience of the Main Contractor appointed to the project. Pre-selection of suitable methods ensured that once construction started, the ‘reactive’ solutions could be implemented quickly and efficiently to minimise impact to schedule. In brief, the selected methods were:
- Expose the karst feature by excavation, ripping and drill & blast (as required) and infill with cement stabilised slurry backfill.
- As above, but backfill with compacted granular fill in a geofabric surround to prevent wash out of fines.
- Drill and grout in areas where high risk GPR anomalies were detected.

5.2 Observational Method

Once rail construction starts, early activities such as establishing borrowing pits, drill and blasting, cutting excavation and foundation preparation, usually expose more of the inherent ground conditions than would be seen in all previous ground investigations. Consequently, construction phase generates considerable, additional opportunities to continually review and update the ground model and risk register and hence manage geotechnical risks. This is particularly the case when additional investigations and risk management activities have been planned to take place during construction.

To take advantage of these opportunities, a geotechnical specialist formed part of the Hope Downs 4 construction support team. They could also draw upon additional specialist support as required. Such ongoing assessment has been termed ‘the Observational Method’, first by Peck [11] and more recently for Pilbara specific projects in works such as [9].

The main components of the observational method that specifically applied to karst risk management were:

- Review of drilling progress and drillers feedback during drill and blast operations. Drill holes were deliberately extended beyond the base of cuts to investigate below rail formation level. Holes were subsequently stemmed before blasting.
- Engineering geological mapping of cuts as they progressed. A simplified example cross section through a cut is provided in Figure 10.
- Inspection of excavations as they progressed, including test pits in areas where coverage was deemed necessary from previous phases of investigation.
- Observing and reviewing geophysical explorations in the base of cuts and incorporating GPR interpretations by the geophysicist into the ground model. See Figure 10 for a simplified example of how anomalies were presented.
- Inspecting the base of cuttings for evidence of karst features.
- Supervising and logging of proof drill holes and drill and grout works in the base of cuts where high risk GPR anomalies had been identified. Open hole drilling using air percussion was used since evidence for karst features can include ‘dropping’ of drill rods into cavities, irregular drilling through infilled cavities, and no / poor return of drilling flush. For the latter, drilling flush can be ‘lost’ into cavities or widened rock joints.

![Figure 10: Simplified section and plan of an example cutting with Ground Probing Radar (GPR) anomalies superimposed](image)

5.3 Remedial Works Completed

A number of karst features were detected and remediated in both the Dolomite and the Calcrete Domains. The pre-established remedial solution selected for each was based on; volume of the feature, depth to base and geometry.

Figure 11 shows a 10m wide cavity within 2m of the rail formation and <3m deep to its base. Being relatively shallow, it was remediated with compacted granular material with a geotextile surround. Note that the visible excavation is wider than 10m as the sides were battered to allow safe access.
Figure 11: Karst remediation by backfilling with compacted granular fill.

Figure 12 shows an approximate 5m long, 2m wide and 5m deep karst feature, again beneath the rail formation. Given the increased depth, a cement slurry infill was used since creating safe access into the feature for compaction of granular material would generate a very large excavation.

For later stages of construction in the Calcrete Domain, drill & blast was not required. Consequently, and to fit with the project schedule, equipment for a drill and grout campaign was mobilised to further manage karst risks in that area. All high risk anomalies identified by GPR surveys were drilled on an approximate 2m primary grid (Figure 13). Drilling progress and injected grout volumes were recorded. Evidence for cavities or ‘broken ground’ included; rates of drilling, drill rods ‘dropping’, loss of drill flush, and if the volume of grout used to backfill an individual drill hole was greater than the volume of the actual hole i.e. grout was ‘lost’ into voids. If cavities were identified, additional secondary and tertiary holes were drilled and grouted. Remediation was deemed complete when;

Figure 13: Probe drilling in areas of GPR anomalies at the base of cuttings. Probe drills were grouted and volumes monitored to further assess potential for voids.

6. OPERATIONS AND MAINTENANCE

Construction of the Hope Downs 4 rail line was completed approximately 12 months ago and it is currently in its operational and maintenance phase. In accordance with the geotechnical risk management framework, the ground model and risk register can remain as ‘live documents’ to inform of karst remedial works completed during construction and to inform of the sections of the rail alignment within karst terrains. Accordingly, asset management / inspection and response regimes can be tailored for these specific locations and assistance sought from the rail design and construction team, including the geotechnical specialist, if required.

7. SUMMARY AND SUGGESTED WAY FORWARD

7.1 General

Management of the karst geo-hazard and associated geotechnical risks for Rio Tinto’s 54km Hope Downs 4 Rail Project followed, as far as practicable, an idealised geotechnical risk management framework that has been advocated internationally by many geotechnical specialists.

The framework is based on there being 3 major contributors to all geotechnical risks. These are; technical risk (inherent ground conditions and how they are interpreted / analysed), contractual risk (or transfer of risk) and project management risk. Therefore, it...
recognises the importance of integrating geotechnical risk management into the broader project management drivers and objectives, and that a systematic and relatively simple approach is required.

For the Hope Downs 4 rail project, communication of geotechnical risk management was via the ground model and risk register. They included engineering geological maps, sections and design tables that split the rail alignment into Domains of similar engineering characteristics. The ground model and risk register were continually updated as additional information became available through the project’s planning, design and construction phases.

The systematic approach was proven to be particularly well suited to the management of karst risks since karst terrain is inherently variable, difficult to investigate and cavities can potentially be encountered anywhere.

7.2 Comments on Investigation Techniques Used

Reasonably ‘standard’ geotechnical investigation techniques were used. They formed a suite of select tools to systematically develop, continually update and communicate the ground model and risk register, and hence manage the karst (and other) risks. Considerable value was gained during the project planning and conceptual design phases by informed and experienced interpretations of available desk study data. The rewards included:

- Early risk identification and planning of associated activities that occurred much later in the project schedule.
- Targeted, focused and specific ground breaking investigations for later phases when more expensive techniques were required i.e. cost effective investigations.
- The potential to involve specialist constructors early in the project and to identify construction methods and forms of contract most suited to the project / works.

For karst terrain, engineering geological mapping, also completed early in the project design phases added considerable value. Significant distances / areas were covered at relatively low cost, accurately defining the extent of the rail alignment that could be affected by karst features. It also created an understanding of their potential frequency and form.

Results from the geophysical GPR surveys were useful, but as anticipated, by no means provided a definitive answers regarding karst feature locations, depths and sizes etc. This is in accordance with expectations from the literature. Potentially, 2-3 geophysical explorations techniques could be used on a given project to provide additional results and for refinement of the overarching ground model. The potential effectiveness of this approach in the Pilbara’s carbonate rocks is worthy of future investigation.

A key benefit provided by the GPR surveys was to enable proof drilling and drill & grout activities to be targeted. Since these are expensive, any ability to refine their use is a value add activity.

Whilst drilling and potentially injecting grout is expensive, there is no disputing the effectiveness of their ability to identify voids and to add confidence regarding accuracy of the ground model. The key consideration, therefore, usually becomes how to ensure such techniques are used in a cost effective, value adding way, rather than if they are applicable.

7.3 Way Forward

Taking into consideration experience gained during karst remediation on the Hope Downs 4 rail project, implementation of the geotechnical risk management framework, as far as practicable, is strongly advocated.

It is recognised that geotechnical risk is only one of the many areas / disciplines that contribute to delivery of rail projects and that all require overarching management by the project manager. Moreover, many external factors e.g. access, approvals, heritage etc, can significantly influence how the various disciplines interface and they can potentially create frequent changes. Therefore, the systematic and simplistic framework used makes integration of geotechnical risk management into the wider project management drivers and objectives easier and more efficient.

With respect to selection, timing and value added by the various methods used on the project (as well as others that are available),
Figure 14: Qualitative review of techniques used (and some others available) for the geotechnical specialist component of the geotechnical risk management framework in Figure 2.

Figure 14 attempts to qualitatively demonstrate a way forward for the geotechnical specialist components of the framework in Figure 2 when used for management of karst risks on heavy haul rail projects in the Pilbara.

7. REFERENCES


