The Value of Comprehensive Geotechnical Information: A Comparison of Pre-Feasibility and Feasibility Study Design Outcomes at the Weld Range Iron Ore Project

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Abstract

The Weld Range Iron Ore Project is located in the Midwest region of Western Australia, and is composed of hematite ore contained within banded iron formation of subvertical orientation. The highly permeable nature of the banded iron units has resulted in deep weathering of the adjacent meta-basic waste rock. Mining of two open pits is proposed, each of approximately four kilometres along strike and greater than 250m in depth.

Initial pre-feasibility geotechnical investigations included the diamond-drilling of holes at average spacings of 500m or greater through the proposed positions of the pit walls. The interpretation of the rockmass conditions from drillhole logging indicated a pseudo-horizontal layering of saprolitic material, weathered rock and unweathered rock, with apparent layers of weaker, intensely weathered material at depth. Geotechnical pit slope design parameters were formulated that were appropriate for the conditions indicated in the pre-feasibility geotechnical model. Based on the perceived uncertainties in this model, recommendations were made for further diamond-drilling investigations, which were carried out during the bankable feasibility study. These holes targeted key areas and reduced the spacing of geotechnical information centres to 300m or less. The information provided by the additional investigations revealed more complex sub-surface conditions than was previously considered. High variability in the thickness of saprolite development became evident, and the patterns of weathering and poor rockmass conditions became more apparent. In order to accommodate these conditions, a significantly different strategy for design of the pit slopes was adopted for the BFS.

1 Introduction

1.1 Project background

The Weld Range Iron Ore Project is located 60 km northwest of the town of Cue in the Midwest region of Western Australia (see Fig. 1). The project includes the Beebyn and Madoonga deposits, separated by a distance of approximately 20 km. The deposits are to be mined by open pit methods, with each pit approximately 4 km long. The proposed Madoonga pit is to be between 250m and 300m deep, whilst the Beebyn pit is to be between 200m and 250m deep. The Beebyn pit will constitute the main focus of this paper.

In 2008, a mining geotechnical evaluation was carried out as part of the pre-feasibility study (PFS). This was followed in 2009 by a bankable feasibility study (BFS), which included further detailed geotechnical study. The main purpose of the geotechnical work in both studies was to provide detailed design recommendations for the slopes within each of the pits. The pit slope design parameters derived for each geotechnical domain served to define the overall slope angles. The parameters included: limiting bench stack heights; widths and positions of inter-ramp safety berms; bench stack angles and inter-ramp angles; bench heights; bench face angles and spill berm widths. The importance of constructing reliable geotechnical models in order to accurately define the design parameters was of paramount importance.
Figure 1. Locality map of the Weld Range Iron Ore Project.

1.2 Site conditions

The Weld Range Iron Ore Project is located in the Weld Range, a long band of ridges extending over a distance of more than 60 km. Steeply-dipping, ENE-striking banded iron formations (BIFs) occur in three ridges at the North, Central and South Weld Ranges. The BIFs are interleaved with meta-basic rocks that show doleritic and lesser basaltic and gabbroic textures. Discontinuous iron mineralisation within the ranges occurs as many separate iron ore lenses. The natural slope angles in the area of the Weld Range vary from less than 5° to greater than 80°. Away from the ridges the topography is very flat.

The geology at the Madoonga and Beebyn deposits is somewhat different. The Madoonga deposit comprises a steeply SSE-dipping rock sequence that includes, from north to south: felsic volcano-sedimentary rocks; a 60 to 250 m thick BIF containing a central shale unit, a 20 to 50 m thick zone of strongly-altered BIF, within which the iron mineralisation is hosted; and mafic igneous rocks, including dolerite and basalt. A sedimentary sequence referred to as canga rests unconformably above the BIF and mineralised units, consisting of ferruginous conglomerate and pisolithic gravels that have a thickness up to 20 m and locally have high Fe grades.

The Beebyn deposit contains numerous steeply SE-dipping BIF units inter-layered with dolerite, of which the most economically important is approximately 40 m thick. The least altered and unweathered BIFs contain millimetre to centimetre-thick bands rich in iron. NW-striking dextral faults with apparent offsets of up to 100m have caused significant segmentation of the rock units and iron mineralisation at Beebyn, as shown in Figure 2. These faults have allowed for preferential weathering and erosion.
The weathering profile overlying the basic igneous rocks has been more strongly developed than over the felsic rocks, with the development of significant horizons of saprolite and weathered rock. Saprolites are silty or clayey materials with soil-like properties, within which the rock texture and structure is preserved, formed by intense, in-situ chemical weathering of the rock. The saprolite material is generally very weak, but locally more competent saprock materials are encountered within the saprolite horizon at Weld Range.

2 Site investigations

The geotechnical field investigation programmes included the drilling, logging, selected sampling and packer (hydrogeological) testing and of oriented, diamond-cored holes.

The drilling during the PFS investigations at each of the Beebyn and Madoonga deposits included 34 geotechnical investigation holes (totalling approximately 8000 m of core), with an additional 19 diamond drilled holes drilled for the resource study (totalling approximately 3500 m of core) that were also geotechnically logged to obtain geotechnical information.

The drilling conducted during the BFS was based on the forward works programme defined during the PFS. It had the aim of achieving greater confidence in the understanding of geotechnical conditions, allowing for a more refined geotechnical model to be interpreted. The additional drilling provided infill information in areas where it had been lacking, and also allowed for targeted investigation of conditions within zones of specific interest (often relating to particular features such as faults). The BFS investigation included 19 holes with a total of 4332m of additional drilling. This consisted of 2442 m of additional drilling (11 holes) at Madoonga and 1890 m (8 holes) at Beebyn.

The outcomes of the BFS investigations at both Beebyn and Madoonga are similar in terms of their impact on the geotechnical domaining and pit slope design rationale. It is therefore appropriate to select only Beebyn pit as the focus for this case study, as it is more structurally complex. The collar locations of the geotechnically-logged drillholes completed during the PFS and BFS investigations for Beebyn are shown with reference to the PFS pit design shell in Figure 3.
3 Identification of Geotechnical Domains

The aim of geotechnical domain modelling is to identify regions of the ground (rock or soil) mass in which geotechnical conditions are expected to be similar, and to define the boundaries between these regions as accurately as possible. This is done in order to facilitate the evaluations for derivation of pit wall design parameters.

The geotechnical domains were identified according the distribution of the major material types and of rock mass quality. The material groups identified for the purposes of geotechnical characterisation for pit wall design at Beebyn included saprolite, dolerite and BIF. These BIF and dolerite have been further divided according to intensity of weathering. Structural failure mechanisms at Weld Range will exert only a localised control on the bench face angles and therefore did not factor strongly in the initial identification of geotechnical domains, although a subsequent pit wall sectorisation was included to account for these design constraints.

Using the existing geological interpretation and the geotechnical drilling data, a set of 3-D wireframe surfaces were created to delineate the geotechnical domains. A comprehensive set of geotechnical properties describing each domain were identified. These included intact rock strength, rock mass classification, rock mass strength, elastic properties, hydraulic conductivity, and the orientation, spacing, persistence and shear strength of structural sets.

Differences in the geotechnical domains interpreted during the PFS and BFS, especially at Beebyn, influenced the slope angles recommendations made.

3.1 PFS domains

The positions of the PFS drillholes and data provided by them supported the interpretation of a pseudo-horizontal layering of saprolitic material, weathered rock and unweathered rock, with apparent layers of weaker, intensely weathered material at depth within the Beebyn Pit. These interpretations are illustrated with reference to the PFS pit profile in the cross section presented in Figure 4.
A wireframe model of the boundaries of this vertical succession of material types was created. At this time the presence and location of the weak zone at depth at Beebyn was inferred and additional data was needed to validate the assumed distribution. The intersections of the geotechnical domain model wireframes with the existing preliminary pit design shell were assessed to identify the likely patterns of materials within the final pit walls and to prepare appropriate slope design parameters. Illustration of the distribution of the geotechnical design domains within the preliminary pit shell at Beebyn is provided in Figure 5.

Figure 4. Sections illustrating the distribution of materials within the pit walls at Beebyn.

The PFS mining geotechnical evaluation provided geotechnical slope design parameters for each of the domains identified within the pit walls. It was identified that the variable thickness and material properties of the saprolite and weak zones domains needed to be more clearly defined during the BFS, since they have a major impact on the design slope geometry and pit slope stability. Improved confidence in the properties of these materials might allow for steeper slope geometry within the pit walls.

Figure 5. Positions of geotechnical domains within the walls of the preliminary Beebyn pit shell.
3.2 BFS domains

Following the drilling and logging of 19 carefully targeted diamond drill holes for the subsequent BFS, the geotechnical models required substantial revision. It was interpreted that the patterns of highly weathered, weak and poor quality rock were associated with deep vertical weathering along the margins of the BIF units at the two deposits, particularly at the positions of the fault dislocations at Beebyn. This interpretation was made possible by careful examination and understanding of the updated structural geology model, weathering data from RC as well as diamond drilling, laboratory testing, as well as the logging of the targeted geotechnical drillholes. Therefore, the weak “layers” interpreted at the toe of the PFS pit shell design are not laterally continuous but are the result of deep vertical weathering. The depth of saprolite and saprock development is correspondingly greater overlying these zones. The revised interpretations are illustrated with reference to the updated pit design profile for Beebyn in the cross sections presented in Figure 6. Due to the high lateral variability, these sections will vary significantly along strike of the orebody, and the two cross sections through the Beebyn deposit illustrate the variability.

Figure 6. Cross-sectional illustration of revised geotechnical domains interpretations at Beebyn.
The re-interpreted models result in a complex pattern of interaction between the geotechnical domains and the pit shells. This is illustrated in Figure 7. The materials likely to be exposed in the pit walls will vary greatly in thickness along strike of the pits, and are highly dependent on the exact position of the pit wall. The pit wall slope designs may need to be significantly altered should the size, width, depth or position of the pits be altered in the future. As a result, a different design rationale was required to achieve practical pit slope design recommendations to deal with this variability.

Figure 7. Illustration of the patterns of materials exposed within the Beebyn pit walls.
4 Revised pit slope design

Instead of simply providing a set of pit slope design parameters for each domain as was done for the PFS, a set of pit sectors were first be identified, for which a most suitable overall pit geometrical configuration was defined. This configuration includes definition of limiting bench stack heights, the positions and widths of inter-ramp berms, and the number and heights of benches within a stack. Where different material types are encountered within a bench stack within each sector, the appropriate bench face angles, spill berm widths and bench stack angles will be selected from the detailed set of slope design parameters recommended for each material type. This new design rationale will be more suitable for dealing with the highly lateral variability in conditions.

Bench stack heights were limited to 50 m within the saprolite materials, and with stacks consisting of 5 benches of 10 m height each. It was considered suitable that bench stack heights of 100 m can be accommodated in the weathered and unweathered rocks of all lithology types, and stacks and with stacks consisting of 5 benches of 20 m height each. In the sectors of the pit where there is considerable horizontal variability between saprolite and weathered rock, it is considered prudent that the heights of bench stacks and individual benches should be restricted to 50 m and 10 m respectively. In sectors with particularly poor geotechnical conditions, up to three stacks of 50 m height, with benches of 10 m height, are required.

To illustrate this design rationale, the re-interpreted domaining /slope sectorisation for the Beebyn main pit is shown in Figure 8, with the corresponding pit geometrical configurations presented in Table 1. The slope angle parameters to be applied for each material type encountered within the pit are listed in Table 2.

![Figure 8. Pit sectors identified within the Beebyn Main Pit.](image-url)
Table 1. Recommended bench stack configurations for Beebyn pit sectors.

<table>
<thead>
<tr>
<th>Design Sector</th>
<th>Stack Number</th>
<th>Depth below Surface (m)</th>
<th>Inter-ramp berm Approx. Position</th>
<th>Limiting Stack Height (m)</th>
<th>Bench Height (m)</th>
<th>Number of Benches</th>
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<tr>
<td>1, 6</td>
<td>1</td>
<td>0 - 50</td>
<td>R.L. 475</td>
<td>50</td>
<td>10</td>
<td>5</td>
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<tr>
<td></td>
<td>2</td>
<td>50 to floor</td>
<td></td>
<td>100 or less</td>
<td>20</td>
<td>5 or less</td>
</tr>
<tr>
<td>2, 4, 5, 7</td>
<td>1</td>
<td>0 - 50</td>
<td>R.L. 475</td>
<td>50</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50 -100</td>
<td>R.L. 425</td>
<td>50</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>100 to floor</td>
<td></td>
<td>50 or less</td>
<td>10</td>
<td>5 or less</td>
</tr>
<tr>
<td>2, 4, 5, 7</td>
<td>1</td>
<td>0 - 50</td>
<td>R.L. 475</td>
<td>50</td>
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<td>R.L. 425</td>
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<tr>
<td></td>
<td>3</td>
<td>100 to floor</td>
<td></td>
<td>50 or less</td>
<td>10</td>
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Table 2. Recommended slope angle parameters per material type for Beebyn.

<table>
<thead>
<tr>
<th>Weathering</th>
<th>Rock Type</th>
<th>Bench Stack Angle (°)</th>
<th>Inter Ramp Angle (°)</th>
<th>Bench Height (m)</th>
<th>Bench Face Angle (°)</th>
<th>SBW Width (m)</th>
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</thead>
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<tr>
<td>Saprolite / Saprocks</td>
<td>40</td>
<td>36</td>
<td>10</td>
<td>65</td>
<td>9</td>
<td></td>
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<tr>
<td>Weathered Dolerite</td>
<td>52</td>
<td>47.5</td>
<td>10</td>
<td>75</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Weathered BIF &amp; Mineralised Material</td>
<td>51</td>
<td>46.5</td>
<td>20</td>
<td>75</td>
<td>13</td>
<td></td>
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<tr>
<td>Unweathered Dolerite</td>
<td>61</td>
<td>56.5</td>
<td>20</td>
<td>85</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Unweathered BIF &amp; Mineralised Material</td>
<td>60</td>
<td>55.5</td>
<td>20</td>
<td>85</td>
<td>12</td>
<td></td>
</tr>
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5 Summary and Conclusions

Following an initial detailed PFS, further investigation during the BFS was considered necessary in order to confirm the geotechnical slope design recommendations for the two large open pits. The aims and outcomes of the additional investigations are summarised below.

- As a result of requirements identified from the PFS, a carefully-targeted and comprehensive drilling investigation was carried out to:
  - densify the geotechnical data and provide data in areas where it was previously lacking,
  - provide information for testing the sensitivity of earlier design assumptions,
  - confirm the initial geotechnical model and assess the validity of the PFS slope design recommendations, and
  - provide clarification for suitable slope design in regions of expected complex conditions.

- As a result of the BFS studies, the geotechnical domaining was re-interpreted from that based on a pseudo-horizontally layered weathering profile to that based on a profile with high vertical and lateral variability.

- The re-interpreted models result in a complex pattern of interaction between the geotechnical domains and the pit shells.

- The materials likely to be exposed in the pit walls will vary greatly in thickness along strike of the pits, and are highly dependent on the exact position of the pit wall.

- The pit wall slope designs may need to be significantly altered should the size, width, depth or position of the pits be altered in the future.

- A different design rationale was required to achieve practical pit slope design recommendations to deal with this variability.

A comparison of the perceived levels of confidence following the PFS and BFS is presented in Table 3.

Table 3. Perceived levels of confidence in Study Information

<table>
<thead>
<tr>
<th>Data Stream</th>
<th>PFS Study</th>
<th>BFS Study</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical data: Rockmass characterisation</td>
<td>Medium</td>
<td>Very high</td>
<td>Good data has been collected concerning the characteristics and properties of the rockmass materials</td>
</tr>
<tr>
<td>Structural interpretation: Major structures</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Structural data: Discontinuity orientations</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Rock material strengths</td>
<td>Medium</td>
<td>Very high</td>
<td></td>
</tr>
<tr>
<td>Rockmass strengths</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Rockmass variability: Domaining</td>
<td>Low</td>
<td>High</td>
<td>Uncertainties in design related primarily to variability of material distributions and properties</td>
</tr>
<tr>
<td>Groundwater conditions</td>
<td>Low</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Slope design recommendations</td>
<td>Medium</td>
<td>High</td>
<td>Slope design includes provision for material variability</td>
</tr>
</tbody>
</table>
The decision by the project owner to proceed with the recommended comprehensive second phase of investigation has resulted in an excellent set of geotechnical and hydrogeological data being obtained. This has allowed for a high level of confidence to be achieved concerning the geotechnical models and the design rationale for providing optimal slope recommendations in complex conditions.

The outcomes of these studies illustrate the importance of the following:

- The need for critical assessment of the uncertainties and assumptions in the initial geotechnical modelling process and outcomes
- Utilisation of a phased approach to investigation, with carefully-targeted investigation in the later phase designed using the results of the earlier phase
- The need for a comprehensive data of suitable density and quality, and also of suitable type and distribution for identification of the key issues that will govern slope design

6 Acknowledgements

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