Cerro Vanguardia (CV) is an Au-Ag mine located in the central steppe of Santa Cruz province, Argentina. The deposit consists of 102 epithermal low-sulphidation veins 19km long, 3.5 - 10m wide and dipping 60° - 90° NE (Heather et al. 2004). Country rock consists of rhyolitic ignimbrites of the Jurassic Age, moderately to intensely fractured and widely altered by hydrothermalism. The stratigraphic sequence dips 7 / 146 on average and comprises stratified, grainy, brecciated and massive slabby ignimbrites. This sub-horizontal stratigraphy is favourable for open pit mining, allowing the excavation of very steep walls which exhibit consistent good performance.

Mining is being carried out mainly through open pits and, more recently, underground longwall developments. Pits are up to 1000m long, 150m wide and 200m deep, with global slope angles of 53° - 58°, 64° - 70° interramps, 20m benches and 6 - 10m berms. Pre-split blasting techniques are widely employed to ensure design compliance under tight dilution constraints, stripping ratio being in excess of 25 (Adamson et al. 2011).

1 INTRODUCTION

Cerro Vanguardia (CV) is an Au-Ag mine located in the central steppe of Santa Cruz province, Argentina. The deposit consists of several veins 3.5-10m wide and 19km long, related to epithermal mineralization of the Chon-Aike formation by Jurassic volcanism episodes. The exploitation is carried out by means of several open pits in the range 100-240m deep. It is to be expected that more than fifty pits will be developed during the lifetime of the project.

The nature of the mineralization process caused different degrees of argillic alteration in the surroundings of the veins, especially in the form of poor quality rock bands that could potentially compromise the stability of the pit walls. Two geotechnical rock-mass characterization programmes were carried out in 2012 and again in 2015 and were employed to perform numerical analyses for slope stability assessments.

This work compares and contrasts the two analysis methodologies implemented for the two studies, with the purpose of showing a data management procedure aimed at reducing uncertainty by several geotechnical procedures. Geostatistical distribution and density of data conditioned the definition of limits between geotechnical units and the accuracy of the boundaries between them. Wide variations both in quality and amount of data implied that key parameters had to be estimated by wholly different methods. Ultimately, enhanced characterization of geotechnical units and the study of detailed analysis sections led to targeted recommendations on excavation procedures and eventually produced a more consistent and reliable pit design.

2 GLOBAL STABILITY ANALYSES

Global and bench-berm stability analyses were performed with the 2D Finite Element Method (FEM) utilizing Phase² (V8) software. General guidelines for stability analyses for open pits were followed from Read & Stacey (2009).

After definition of geotechnical domains and model, critical sections for each pit were defined based on their heights and general inclination angle; only the most unfavorable cases were simulated. Typical pit geometries presented 100 - 200m depths, 15 - 20m high benches, berm widths between 4 and 6m and bench inclinations from 75° to 87°.

The procedure consisted of the simulation of the excavation process according to the exploitation program. Initial stresses were calculated with the K₀ procedure, assuming Kₓ = Kᵧ = 1.0. Since no in-situ measurements were available, sensitivity analyses were performed in order to assess the implications of this assumption; as expected, in-situ initial stresses
have a negligible effect on the results of 2D numerical analyses of slope stability.

Rock-mass features and minor discontinuities were considered in the analysis by the standard procedure of reducing the Hoek-Brown strength parameters for each geotechnical domain. According to the blasting methodology applied and guidelines put forth in Hoek (2012), a damage factor (D) equal to 0.7 was considered in a zone adjacent to the pit face.

The global factor of safety (FoS) was determined by using the shear strength reduction factor methodology (SRF). Stability was analysed at global scale, with a deterministic approach and an acceptance criteria for overall slopes: FS > 1.3. Where appropriate, modifications to the geometry were proposed to comply with adopted safety requirements and the project’s excavation to date.

3 SITE-WIDE GEMECHANICAL DATABASE

3.1 Geology

The Cerro Vanguardia epithermal Au-Ag deposit is situated within the Deseado Massif (De Giusto et al. 1980). It encompasses a 60,000km² area in which Jurassic volcanism is the predominant episode, associated with the rifting originated in the Atlantic Ocean opening (Uliana et al. 1985). Heather et al. (2004) have performed the latest geological study of Cerro Vanguardia Project, according to which the deposit consists of 102 epithermal low-sulphidation veins mineralised with Au and Ag, stored in rhyolitic ignimbrites of the Jurassic Age. Veins span a length of 193km, measure 3.5m in width on average (10m maximum) and dip 60° - 90° NE. Mineralization generally occurs as veins and stockworks, together with quartz, chalcedony, opal, baryte, calcite and adularia.

Hydrothermal alteration mostly comprises silicification, sericitization, adularization, argillitization and propylitization. Alteration minerals are adularia, sericite-illite, smectite and kaolinite (Zubia et al, 1999).

Site stratigraphy consists of a repetitive series of felsic ignimbrites divided into stratified, grainy, brecciated (subdivided into base breccia, breccia and superior stratified) and massive slabby (composed of seven subunits).

3.2 Major structures

Within the Cerro Vanguardia anticline, the stratigraphic sequence dips 7° (on average) in direction 146 SE (Heather et al. 2004). Faults oriented 324° / 85° determine the general fracturing of the rock mass, moderate to intense, with clear fracture patterns. The main direction at mine scale is 328° / 87°.

Fractures with densities greater than 5 per metre have a marked principal direction, namely 323° / 85°, which correlates them directly to veins and veinlets (dominant orientations are respectively 323° / 86° and 323° / 89°).

3.3 Intact Rock

Previous characterization of intact rock units (IRUs) presented in Hormazábal et al. (2004) was based on geotechnical mappings and laboratory tests on core drilling performed at four pits. In order to simplify stability analyses for a multi-pit mine, Hormazábal et al. (2004) suggested sorting the rock mass into simple categories that grouped similar mechanical properties. These basic geomechanical units (BGUs) were classified according to their degree of alteration into soft argillic, soft, and hard, the latter being subdivided into three subcategories (small blocks, big blocks, massive), in relation to the degree of fracturing of the rock mass (see Table 1). In addition, recent geotechnical reports have included a subdivision of the Soft unit on the basis of fracturing.

Table 1. Summary of the geotechnical units of CV.

<table>
<thead>
<tr>
<th>Geotechnical unit</th>
<th>Alteration</th>
<th>Fracture frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Argillic</td>
<td>Argillic (intense)</td>
<td>—</td>
</tr>
<tr>
<td>Soft</td>
<td>Argillic (light)</td>
<td>—</td>
</tr>
<tr>
<td>Hard – Small blocks</td>
<td>Siliceous</td>
<td>Medium</td>
</tr>
<tr>
<td>Hard – Big blocks</td>
<td>Siliceous</td>
<td>Low</td>
</tr>
<tr>
<td>Hard – Massive</td>
<td>Siliceous</td>
<td>Very Low</td>
</tr>
</tbody>
</table>

More recently, this data set was augmented by a series of test results made available in 2012 and 2015: 68 uniaxial compression, 16 tension, 121 triaxial, 23 Young’s modulus and 239 unit weight tests. Samples were taken from several veins, both on the footwall, hangingwall and the orebody itself. Materials encompass grainy, brecciated and slabby ignimbrites, as well as argillic and siliceous alterations.

Those new tests contained a fair description of the lithology, albeit not of the alteration degree or type. Therefore, in the 2012 and 2015 analyses described herein, intact rock and geotechnical units as defined in (Hormazábal et al. 2004) could not be retained and had to be redefined according to the data available.

4 THE 2012 DATABASE AND PROCEDURE

4.1 Rock matrix

Scanlines were the only source for rock mass characterization and definition of geotechnical domains, and they only included lithology, not alteration. Thus, IRUs were redefined for each pit, individually, on the basis of lithology/stratigraphy and then subdi-
vided according to matrix strength into “Soft” and “Hard” (see Table 2). Strength parameters were obtained by fitting Hoek-Brown failure envelope to test results; given the small size of the database available for each unit, the parameter $m_i$ was adjusted in accordance with reference values for each lithology.

Table 2. 2012 Intact Rock Units for ODcb7.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Strength</th>
<th>$\sigma_{ci}$ [MPa]</th>
<th>$m_i$ [—]</th>
<th>$E_i$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBR*</td>
<td>Soft</td>
<td>46.4</td>
<td>15.4</td>
<td>18850</td>
</tr>
<tr>
<td>IBR*</td>
<td>Hard</td>
<td>65.3</td>
<td>26.1</td>
<td>32800</td>
</tr>
<tr>
<td>IGR**</td>
<td></td>
<td>115.0</td>
<td>26.0</td>
<td>43400</td>
</tr>
</tbody>
</table>

* IBR: brecciated ignimbrite
** IGR: grainy ignimbrite

4.2 Discontinuities

Structural domains were defined on the basis of discontinuity data captured by line mappings and validated through geological interpretation of pit wall photographs.

4.3 Rock mass

The rock was classified with Bieniawski’s Rock Mass Rating (Bieniawski 1989), which was calculated for each structural set: the lowest RMR$_{89}$ was regarded as controlling rock mass instability and the rest were ignored. Additionally, the rating adjustment for discontinuity orientation was applied for each pit, on a case-by-case basis.

Intact rock strength for RMR calculation was taken as that informed in scanlines, which indicated lithology but not alteration. Where available, it was complemented with lab test data, albeit it is worth noting that important differences were observed between the two. Roughness rating was based on the joint roughness coefficient (Barton 1973).

The Hoek-Brown strength criterion was employed for the rock mass. GSI was calculated as “dry” RMR$_{89} – 5$ (Hoek 1994).

5 THE 2015 DATABASE AND PROCEDURE

The quantity, quality and spatial distribution of the data available in 2012 proved insufficient to fully address the uncertainties in material rock properties, implying that large ranges of values had to be considered for the sensitivity analyses of each parameter, yielding a poorly defined risk scenario. This fact motivated the execution of additional exploration studies aimed at enriching the geomechanical characterization. A fairly large set of non-oriented drill holes and additional mappings were performed. As a result of this field effort, a much enlarged and consistent database was accessible in 2015.

5.1 Rock matrix

Hormazábáel et al. (2004) defined IRUs on the basis of fracturing. In the light of later (2003 and 2011) tests, the authors have not observed differences in intact rock characteristics that could be ascribed to block size, except for the Hard Massive unit. In other words, fracturing could not be directly attributed to intact rock behavior that could be inferred from it. On the other hand, definition of geotechnical domains was based on corelogs complemented with mappings, all of which contained UCS data but scarcely any lithology or alteration. Therefore, 2015 IRUs shown in Table 3 were classed solely on strength: each unit was enriched with new lab tests and thus the confidence interval 95% for the mean was diminished. It is acknowledged that this classification deserves further attention, observation of the pit walls while mining being the most direct method of improving the consistency of the approach.

Table 3. 2015 Intact Rock Units.

<table>
<thead>
<tr>
<th>IRU</th>
<th>$\gamma$ [kN/m$^3$]</th>
<th>$\sigma_{ci}$ [MPa]</th>
<th>$m_i$ [—]</th>
<th>$E_i$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Argillic</td>
<td>22.1</td>
<td>11.4</td>
<td>12.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Soft</td>
<td>23.0</td>
<td>21.6</td>
<td>14.8</td>
<td>15.8</td>
</tr>
<tr>
<td>Hard</td>
<td>24.2</td>
<td>41.1</td>
<td>15.6</td>
<td>21.9</td>
</tr>
<tr>
<td>Hard Massive</td>
<td>25.0</td>
<td>73.2</td>
<td>23.3</td>
<td>22.5</td>
</tr>
</tbody>
</table>

5.2 Rock mass

Rock mass characterization was primarily based on non-oriented geotechnical core logging, which constituted the most abundant geomechanical information source. Scanlines and mappings were also available and mainly employed to validate GSI and UCS obtained from corelogs.

The system described in (Dempers et al. 2010) was used for logging the cores. This methodology enables the direct computation of RMR$_{80}$ (Laubscher 1990), Q (Barton 1974) and GSI (Hoek 1995). These parameters were determined for 3m core runs. The direct computation of GSI is not optimal when it comes to large databases, as it requires the use of charts. Therefore, GSI was estimated as “dry” RMR$_{89} – 5$ (Hoek 1994).

The estimation of UCS, RQD, spacing and groundwater ratings for RMR$_{89}$ was straightforward. Conversely, to calculate $J_c$, an equivalence had to be established with the ratings defined in (Dempers et al. 2010). In particular, persistence and weathering were lacking and had to be adopted from scanlines.

In (Dempers et al. 2010), the joint ratings are categorized by the following angles of incidence: 0 - 30°, 30 - 60° and 60 - 90°. Accordingly, one RMR$_{89}$ was calculated for each group and the minimum was adopted. As usual, the synthesis of large amounts of experimental data into a small set of indexes simplifies the picture at the cost of loss of detail and sophistication. Observation of the pit walls will also al-
low for the refinement of the proposed classification procedure for Cerro Vanguardia pits.

Figure 1 (left) presents the RMR$_{89}$ obtained under these assumptions, alongside RMR$_{89}$ for $J_c = 10$ and for $J_c = 20$. As shown, the foregoing considerations are equivalent to considering $J_c < 10$. Figure 1 (right) shows the variation of RMR$_{90}$ and RMR$_{89}$ (for joint groups). In all cases, RMR$_{90}$ and RMR$_{89}$ follow the same general trend, except for outliers.

Figure 1. Left: RMR$_{89}$ calculated for $J_c = 10$ and for $J_c = 20$. Right: RMR$_{90}$ and RMR$_{89}$ for three joint groups.

6 APPLICATION TO PIT OSVALDO DIEZ CUTBACK 7

Pit Osvaldo Diez is one of the main producers of the Cerro Vanguardia operation. Mining in this location started in 2002 and continued uninterrupted since then. Several cutbacks were performed. The authors were involved in the design and analysis of Cutback 7, which is employed here as an example of the application of the two material databases to a single problem.

Analyses completed in 2012 and 2015 for pit Osvaldo Diez Cutback 7 (ODcb7, Fig. 2) are compared and contrasted. The section analyzed in 2012 almost coincides with the Domain 2 section defined in 2015.

Domain 2 comprises highly altered rock in the uppermost 20 - 30m, underlain by competent rock. According to core log data, fracturing is medium to low (RQD > 50) without any major gouge bands. Fracturing does not correlate with the degree of alteration: RQDs of 80 - 100 have been recorded for cores having UCS < 5MPa (unconfined compressive strength estimated via Schmidt hammer).

In both 2012 and 2015 analyses, staged excavation of the cutback was simulated by 2D finite element models in Phase 2, where each stage was allowed to converge to full equilibrium before the new stage was simulated. A shear strength reduction calculation was carried out at the final stage to assess the FoS of the final intended wall.

Figure 2. Plan view of ODcb7 pit and sections analyzed.

6.1 2012 analysis

Available information in 2012 consisted of four 20m-long scanlines distributed between levels 185 and 205. A unique domain was defined and therefore, the critical section was that with the steepest geometry (Fig. 3). Geomechanical parameters and mesh considered in the FEM simulations are informed in Table 4 and Figures 4-5 respectively.

The Young’s modulus for the rock mass was estimated via (Hoek & Diederichs, 2006): $E_{mr} [MPa]= E_i [MPa] \cdot \left( 0.02 + \frac{1-D/2}{1+ e^{[(60+150 -GSI)/13]}} \right)$

A Poisson ratio equal to 0.26 was considered for all geotechnical units. The FoS calculated for the final excavation was 1.63. Shear strains corresponding to the FoS stage are displayed in Figure 6.

Table 4. Geomechanical parameters, 2012.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>$\gamma$ [kN/m$^2$]</th>
<th>GSI</th>
<th>$\sigma_{vi}$ [MPa]</th>
<th>$m_i$</th>
<th>$E_i$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBR Soft</td>
<td>26.0</td>
<td>44</td>
<td>46.4</td>
<td>15.4</td>
<td>18.9</td>
</tr>
<tr>
<td>IBR Hard</td>
<td>26.0</td>
<td>44</td>
<td>65.3</td>
<td>26.1</td>
<td>32.8</td>
</tr>
<tr>
<td>IGR</td>
<td>26.0</td>
<td>44</td>
<td>115.0</td>
<td>26.0</td>
<td>43.4</td>
</tr>
</tbody>
</table>
6.2 2015 FEM simulation

On top of the database available in 2012, additional information provided by eight loggings was produced for the 2015 analyses, which enabled the definition of five geotechnical domains. Fortuitously, the section analyzed in Domain 2 (Fig. 7) almost coincided with the section studied in 2012.

Geomechanical parameters and mesh considered in the FEM simulations are informed in Table 5 and Figure 8-9 respectively. Rock mass Poisson’s ratio and Young’s modulus are estimated considering Hoek et al (2000) and Hoek & Diederichs (2006), respectively.

The FoS calculated for the final excavation was 1.24. An alternative geometry was proposed by widening the benches up to 10m at levels +95 and +115masl; the corresponding FoS was 1.36. Shear strains corresponding to the safety calculation stage are displayed in Figure 10.
Two analysis methodologies were presented for the stability assessments of pit Osvaldo Diez cutback 7 at Cerro Vanguardia mine, Santa Cruz Province, Argentina. The geological, structural and rock mass model at deposit scale were outlined, which form the basis for the analyses performed in 2012 and 2015. The respective databases were compared and contrasted along with the processes and criteria that were implemented to obtain the relevant mechanical parameters.

The stability analysis performed in 2012 showed a very robust Factor of Safety 1.63 but a wide uncertainty coming from many sources, mainly the quantity, quality and spatial distribution of the data available. This fact motivated the execution of additional exploration studies to enrich the geomechanical characterization; thus a much enlarged database was accessible in 2015.

The stability analysis performed in 2015 for the same pit wall showed a Factor of Safety 1.26. While 1.26 is much lower than 1.63, the uncertainties related to the 2015 analysis were much less than those of the 2012 study; scatter was lower, and ultimately the confidence in the design was higher. Furthermore, the finer detail of the geomechanical characterization of the rock mass allowed for a slight change in the wall design which raised the Factor of Safety to 1.36, a value deemed reasonable for this wall and remaining level of uncertainty.

The improvement of the geotechnical database — both at deposit and at pit scale— and the study of numerous and detailed analysis sections led to targeted recommendations on excavation procedures and, at times, slight variations in slope geometry which eventually produced a more consistent and reliable pit design.

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