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Impacts of geotechnical characterisation on stability analyses: a case study in a Chilean open pit mine

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Abstract

Geotechnical characterisation aims to subdivide the rock mass into domains with similar geotechnical properties, for which classification systems such as the Rock Mass Rating (Bieniawski 1973), Q-system (Barton et al. 1974) and geological strength index (GSI) (Hoek 1994; Hoek & Brown 1997) have been developed.

One common methodology for estimating geotechnical parameters involves creating a geostatistical model based on surface and drillcore mapping, which can lead to overestimations or underestimations due to limited spatial data, resulting in higher uncertainty. Another approach could be to assume homogeneity within defined geotechnical domains and subdivide them as more data becomes available, but this can lead to reliability issues if the more heterogeneous units are under sampled.

The chosen approach impacts stability analyses, even when dealing with the same rock mass. A rock mass quality model with low reliability results in an excessively conservative or, conversely, overly optimistic analysis. With uncertainty, a more conservative analysis is typically chosen.

This paper presents, as a case study, an approach used for representing rock mass parameters applied to the numerical stability analysis of an open pit mine located in Chile, addressing the difficulties encountered and the mitigation measures applied for each methodology to estimate the GSI. The results validate the approach currently implemented, which is based on deterministic modelling of a separate poor-quality domain using variables captured by drilling (rock quality designation), alteration, lithology, structure mapping). This approach has provided a higher level of reliability in predicting poor-quality areas and, consequently, a reduction in the uncertainty of future scenarios.

Keywords: *geotechnical characterisation, rock mass quality, slope stability, numerical modelling*

1 Introduction

Geotechnical characterisation is the initial stage of any stability analysis. It allows subdivision into domains of similar geotechnical behaviour, simplification of inherent heterogeneities and uncertainties, and estimation of the geotechnical parameters of each domain, making subsequent work more manageable. Commonly used rock mass classification systems, such as the Rock Mass Rating, Q-system and geological strength index (GSI) (Bieniawski 1973; Barton et al. 1974; Hoek 1994; Hoek & Brown 1997), are tools that help quantify characteristic parameters of rock mass quality – understood as the degree of fracturing and/or alteration – thereby determining the in situ geotechnical conditions.

Given the inherent difficulties of obtaining field data from surface and drillcore mapping, geostatistics have been extensively employed to estimate geotechnical parameters at larger scales (where direct access is not possible). This discipline allows the generation of spatial variable models based on limited field data, using mathematical techniques and stochastic realisations to project this information onto unknown areas (Chilès & Delfiner 2012). Typically, the output of this process is a block model that reflects the spatial distribution of geotechnical variables of interest.

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While the application of geostatistical methods aims to predict parameter distributions within the rock mass and account for its heterogeneity, it also seeks to reduce inherent uncertainty. However, these models may still deviate from field data, often resulting in low-confidence inputs for subsequent analyses such as stability analyses. Consequently, representations may vary between overly conservative and insufficiently conservative scenarios of rock mass behaviour, impacting subsequent analyses.

The ideal solution would be to incorporate field data until the model achieves the desired reliability. However, this process is both time consuming and costly. Given the urgency of many engineering processes requiring rapid responses, such analyses can become critical, with downstream impacts that are often difficult to quantify.

Another commonly used approach, due to its simplicity, is to assume that defined geotechnical domains are spatially homogeneous and assign design geotechnical parameters to these units. As more field data becomes available, these domains can be subdivided and redefined. However, this method has the drawback that domains with high variability – and insufficient data to justify subdivision – may lack adequate representation in the database.

Regardless of the method for estimating rock mass parameters, proper calibration helps to a degree by capturing and accounting for specific gaps in the geostatistical model. Based on field observations, such adjustments can help reproduce historical behaviours and calibrate material properties, thereby improving the reliability of predictions. Nevertheless, these assumptions must be reasonably applied and supported by field data; otherwise, they will not enhance the reliability of predictive stages. Moreover, predictive stages will not benefit from this hindsight, and any gaps that are identified and corrected in the calibration can be expected to occur in future stages.

This study presents, as a case study, the evolution and comparison of different geotechnical characterisation methodologies for the GSI in an open pit mine in Chile, and how the chosen characterisation approach has influenced the results of numerical models focused on slope stability. The findings from various analysis cycles have led to new approaches for stability modelling and, consequently, GSI characterisation. This has been driven and validated – to some extent – by the most recent approach implemented at the mine. By characterising poor-quality zones within each geotechnical domain, based on parameters obtained from drilling (rock quality designation [RQD], alteration, lithology, structural mapping, etc.), the representation and reliability of critical zones from a geotechnical perspective have been improved, thereby reducing uncertainty in predictive analyses.

2 Approaches to geotechnical characterisation and its effects on stability analyses in a Chilean mine

The open pit mine is characterised by two distinct geological settings: one is a porphyry copper-type environment where the rock mass is generally competent; the other is epithermal type comprising zones of poor to very poor geotechnical quality associated with highly fractured areas and the presence of argillic alteration. The northern and northeastern parts of the pit are dominated by sedimentary-volcanic rock sequences, while the deeper sections are composed of more competent intrusive rocks with early-stage alterations.

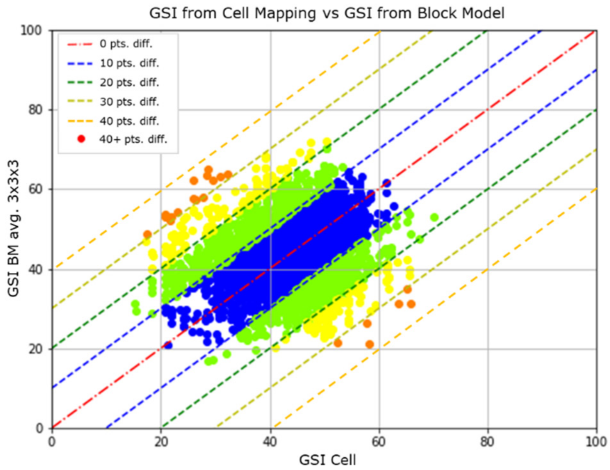
Data collected through surface and drillcore mapping has revealed significant spatial variability in rock mass quality across different sectors of the pit. Historically, this has posed a constant challenge for geotechnical characterisation as it is responsible for capturing this variability within an acceptable degree of accuracy – something that directly impacts subsequent analyses such as stability assessments.

The geotechnical characterisation approach using block models has typically been employed at the mine. However, there have been challenges in aligning the block model's predictions with field data, particularly in zones of poor geotechnical quality. These areas are especially sensitive as they have played a role in slope failures controlled by the strength of the rock mass.

Data from block models has been compared with cell mapping data, where each mapped location has been contrasted against adjacent data from the block model. A search volume of 3 × 3 × 3 blocks – forming a cube of 27 blocks, each side being three blocks-long – was used, with the central block being the one closest to the centroid of the mapped cell. Each block typically measures from 15 × 15 × 10 m to 20 × 20 × 15 m, while a typical cell covers an area of 15 × 10 m. However, for some cells, dimensional data is not available in the database.

As an example, Figure 1 shows a comparison between the GSI from cell mapping and the average GSI from a block model within a 3 × 3 × 3 block search volume. It was observed that within the GSI range of 30 to 45, the block model overestimates values by more than 10 points in 26% of the cells. For GSI values below 30 – which indicate a rock mass with higher levels of alteration and fracturing – this percentage increases to 78%.

Introducing a block model with these characteristics as input for any type of stability analysis – particularly where low GSI areas have controlled instabilities in the past – will inevitably lead to deviations in the results. Section 4.1 delves deeper into numerical stability analyses derived from the direct use of this block model.



	Cells with				
Abs. Diff.	GSI [0, 30)	GSI [30, 45)	GSI [45, 60)	GSI [60, 100]	TOTAL
10 pts.	21.57%	73.47%	80.13%	15.4%	74.32%
20 pts.	52.67%	23.77%	17.14%	49.15%	21.69%
30 pts.	20.42%	2.66%	2.64%	29.11%	3.62%
40 pts.	5.34%	0.1%	0.09%	6.34%	0.37%
+40 pts.	0.0%	0.0%	0.0%	0.0%	0.0%
TOTAL	100.0%	100.0%	100.0%	100.0%	100.0%

Figure 1 Comparison of the geological strength index (GSI) values obtained from cell mapping versus those reported by the block model (BM), considering a 3 × 3 × 3 block search volume around the cell

Another approach that has been evaluated – and is commonly used due to its simplicity – is the definition of geotechnical domains (also called units) under the assumption that they are spatially homogeneous, where an average GSI value is assigned to each domain. In the case of the mine, as more data has been collected over time, domains have been subdivided to reach a total of 12 geotechnical units to date. No further subdivisions have been made due to the current sufficiency of information supporting their definitions. This is not only dependent on the amount of available mapping data but also on the number of intact rock tests conducted, which are essential for distinguishing between similar lithologies.

Intact rock tests typically form a more limited database compared to what is considered sufficient for characterising geotechnical units. As a result, it becomes more difficult to subdivide units in a way that acceptably represents – depending on the intended purpose – the behaviour of the rock mass. Consequently, a higher level of uncertainty and variability is generally accepted.

This approach, therefore, has a disadvantage in that it can lead to reliability issues when geotechnical units exhibit high spatial variability in their properties but are not adequately represented due to insufficient data to justify further subdivision – something that can be highly likely, depending on the project.

In Figure 2a, GSI values indicated by cell mapping are plotted. In Figure 2b, geotechnical units are spatially distributed by a block model and a mean GSI value is assigned to each unit. Then this is compared with cell mapping. Areas with a GSI below 30 points are under-represented by the geotechnical units derived from the block model. At the same time, areas above 30 points are clearly over-represented in the block model.

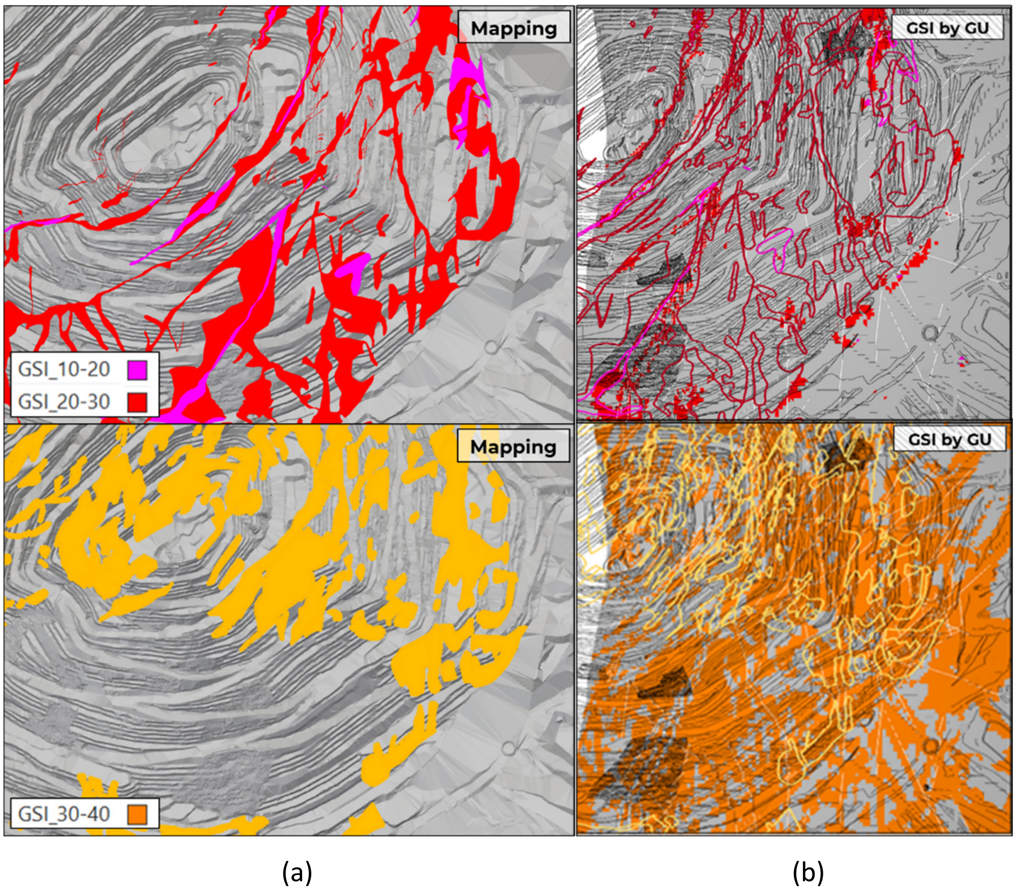


Figure 2 Areas with a geological strength index (GSI) in the ranges of 10–20 points (magenta), 20–30 (red) and 30–40 (orange) according to (a) cell mapping and (b) mean GSI value assigned to each geotechnical unit

A direct implication of the deviations observed in geotechnical characterisation models is that, when designing a slope assumed to be in a poor-quality rock mass, a more conservative design is typically adopted (i.e. flatter slope angles). However, if it is later confirmed that the rock mass was of better quality, this results in a missed opportunity to implement a less conservative design (steeper slope angles), which directly impacts the mine plan and overall project value. Conversely, assuming a rock mass is of fair to good quality when it is in fact poor or very poor not only poses a risk to the mine plan and project value but also, more importantly, introduces a safety risk due to potential instabilities that could lead to irreparable consequences including loss of life.

Stability studies (analytical, empirical, stochastic and numerical) conducted over various analysis cycles have helped highlight discrepancies between geotechnical characterisations derived from block models and those based on field data (surface and drillcore mapping). These discrepancies have had to be addressed through previously discussed and agreed-upon assumptions. However, they have indirectly reduced the reliability of predictive scenarios, ultimately impacting the mine plan.

With the aim of improving the representation of areas with poor to very poor geotechnical quality (GSI below 30 points) – initially for geometallurgical purposes – a separated domain of highly altered and fractured rock was modelled. This was based on variables captured through drilling, such as RQD (Deere 1964), alteration, lithology and structural mapping. This model, referred to as the poor-quality zone model (PQZM), enabled the redefinition of the geotechnical units both within and outside this domain. It helped reduce GSI variability within each new geotechnical unit, resulting in a smaller number of more clearly differentiated units, not only in terms of the GSI but also in other variables such as uniaxial compressive strength.

3 New approach to geotechnical characterisation

The PQZM was constructed based on drillcore intervals identified as having poor geotechnical quality. This classification was made using criteria such as the presence of faults, hydrothermal breccias and non-cohesive breccias, among others. The initiative was initially developed for geometallurgical purposes.

To build the model, data from drillhole logs (RQD, alteration and lithology) and field mapping (structures, alteration and lithology) were used as inputs. The data was analysed collectively, grouping similar conditions in terms of fracturing and alteration. This led to the definition of four descriptive categories (1 to 4), as shown in Table 1. Based on these descriptions, categories 1 and 2 were selected as indicators of poor geotechnical quality, which together define the PQZM. Figure 3 spatially displays the different categories (1 to 4), highlighting the extent of the PQZM.

Table 1 Categories for grouping field data and the likelihood of finding poor geotechnical quality

Category ID	Description (probability of poor-quality zone)
1	Presence of fault, fault zone, highly fractured (high probability)
2	High degree of fracturing, damaged zone (probable)
3	Fractured (low probability)
4	Slightly to non-fractured (very low probability)

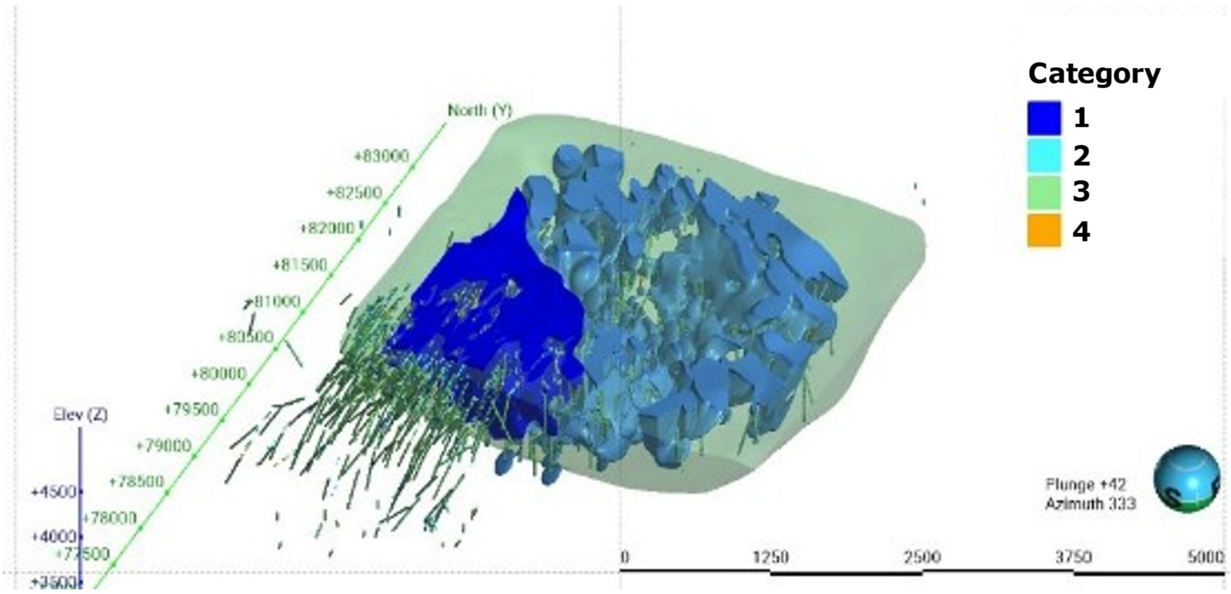


Figure 3 Spatial distribution of categories 1 to 4. 1 and 2 constitute the poor-quality zone model

Afterwards, a possible influence of the poor geotechnical quality areas on the geotechnical parameters – such as degree of fracturing – of each geotechnical unit was analysed. It was observed that RQD mapped from drillcores within the PQZM had lower mean values than outside of it. This was also reflected in their probability distributions, with this behaviour being consistent across all geotechnical units. As an example, Figure 4 shows the probability distribution of RQD for a particular geotechnical unit.

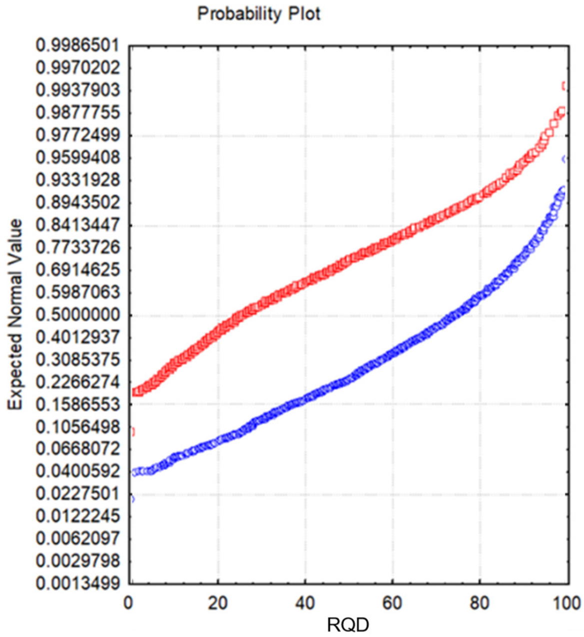


Figure 4 Probability distribution of rock quality designation (RQD) outside (red) and inside (blue) the poor-quality zone model in a geotechnical unit of the mine

Over time, the PQZM was progressively updated to incorporate new geological and geotechnical information as well as new variables – such as arsenic grades from blasthole data. This variable was included due to the observed relationship between high concentrations of arsenic and proximity to structures with a certain degree of alteration, which is attributed to arsenic's tendency to remain in hydrothermal fluids rather than precipitating.

After several prior analyses, the PQZM was used to redefine the geotechnical units. In addition to the typical classification variables such as lithology, alteration and mineralisation, the spatial location inside or outside the PQZM was also established as a key criterion.

This redefinition resulted in a new set of geotechnical units; fewer in number compared to the previous classification and more clearly distinguishable from one another. It also led to a reduction in GSI variability within each geotechnical unit. Figure 5 shows the distribution of the GSI inside and outside the PQZM for each of the new geotechnical units.

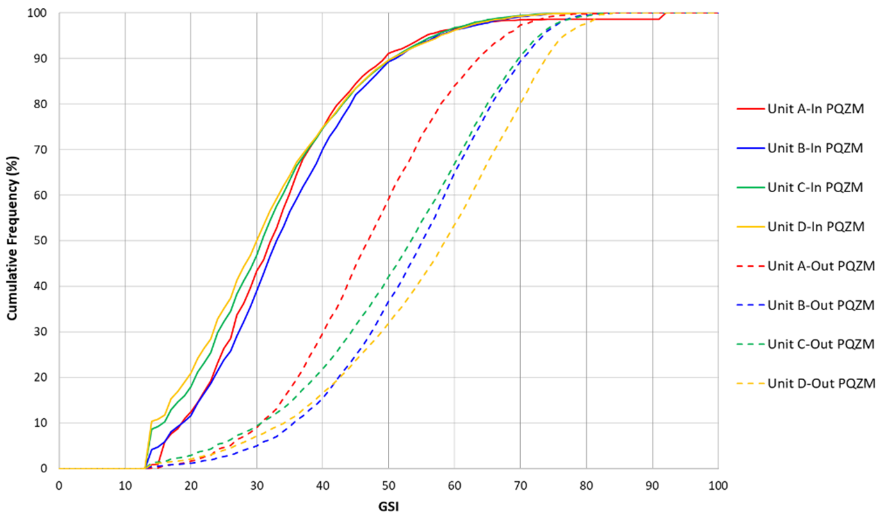
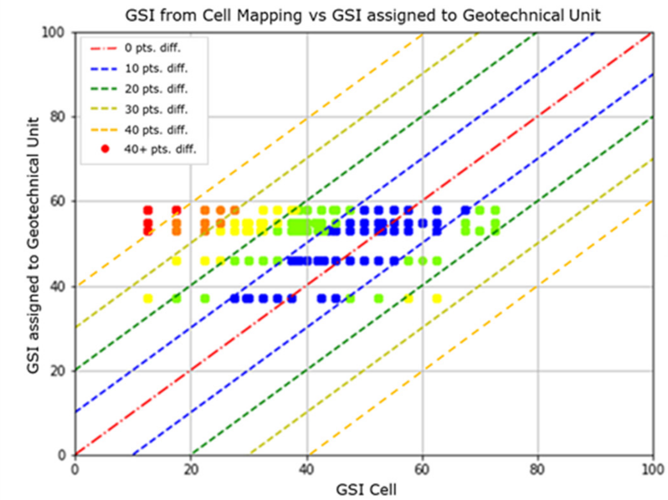


Figure 5 Cumulative frequency plot of the geological strength index (GSI) for the new geotechnical units, inside and outside the poor-quality zone model

In the same way as with the previously presented approaches, an alignment assessment was carried out between the PQZM and the surface mapping data, comparing the GSI assignment by geotechnical unit and its spatial distribution within a neighbourhood around the point indicated by cell mapping. However, in this case, the comparison was performed separately, considering values inside and outside the PQZM.

For the rock mass outside the PQZM, as shown in Figure 6, 35% of the assessed cells show a difference of no more than 10 points when using the median (50th percentile) as the representative GSI value, while 45% of the cells fall within a 20-point difference. This outcome improves significantly when using the 35th percentile properties, where differences greater than 10 points are observed in only 31% of the cells.

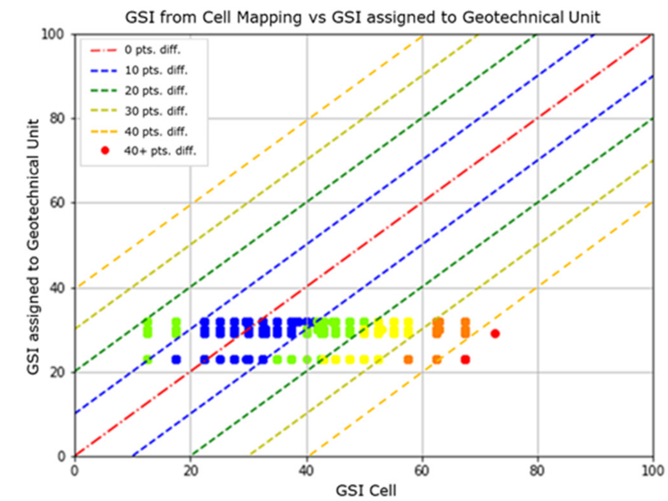
On the other hand, for the rock mass within the PQZM (Figure 7), 59% of the cells show a maximum difference of 10 points and another 32% show a difference of up to 20 points when using the 50th percentile GSI as representative. However, when the 35th percentile is used, the proportion of cells with a 10-point difference drops to 41%, while those with a 20-point difference increase to 43%.



GSI P_{50}	Abs. Diff.	GSI [0,30)	GSI [30,45)	Cells with GSI [45,60)	GSI [60,100)	GSI [0-100]
	10 pts.	2.8%	16.8%	87.0%	84.5%	35.2%
	20 pts.	25.8%	62.1%	12.8%	14.6%	44.6%
	30 pts.	45.1%	21.1%	0.2%	0.9%	17.6%
	40 pts.	25.0%	0.0%	0.0%	0.0%	2.5%
	+40 pts.	1.3%	0.0%	0.0%	0.0%	0.1%
	Total Distrib.	10.1%	61.6%	27.1%	1.2%	100.0%
	Mean Error	25	14.0	3.5	-8	12.0

GSI P_{35}	Abs. Diff.	GSI [0,30)	GSI [30,45)	Cells with GSI [45,60)	GSI [60,100)	GSI [0-100]
	10 pts.	22.2%	66.0%	95.4%	0.0%	68.7%
	20 pts.	56.9%	34.0%	4.6%	94.8%	29.1%
	30 pts.	19.9%	0.0%	0.0%	5.2%	2.1%
	40 pts.	1.0%	0.0%	0.0%	0.0%	0.1%
	+40 pts.	0.0%	0.0%	0.0%	0.0%	0.0%
	Total Distrib.	10.1%	61.6%	27.1%	1.2%	100.0%
	Mean Error	16	8.7	-2.1	-14	6.2

Figure 6 Comparison of assigned geological strength index (GSI) (50th percentile) values in geotechnical units outside the poor-quality zone model with cell mapping. In the graph, each row corresponds to a geotechnical unit



GSI P_{50}	Abs. Diff.	GSI [0,30)	GSI [30,45)	Cells with GSI [45,60)	GSI [60,100)	GSI [0-100]
	10 pts.	91.9%	66.9%	0.0%	0.0%	59.3%
	20 pts.	8.1%	33.0%	52.7%	0.0%	32.1%
	30 pts.	0.0%	0.1%	46.8%	0.0%	8.0%
	40 pts.	0.0%	0.0%	0.5%	99.2%	0.6%
	+40 pts.	0.0%	0.0%	0.0%	0.8%	0.0%
	Total Distrib.	16.7%	65.7%	17.0%	0.5%	100.0%
	Mean Error	6	-7.1	-20.2	-33	-7.3

GSI P_{35}	Abs. Diff.	GSI [0,30)	GSI [30,45)	Cells with GSI [45,60)	GSI [60,100)	GSI [0-100]
	10 pts.	99.2%	37.5%	0.0%	0.0%	41.2%
	20 pts.	0.8%	62.4%	9.4%	0.0%	42.8%
	30 pts.	0.0%	0.1%	79.5%	0.0%	13.6%
	40 pts.	0.0%	0.0%	11.1%	90.9%	2.4%
	+40 pts.	0.0%	0.0%	0.0%	9.1%	0.0%
	Total Distrib.	16.7%	65.7%	17.0%	0.5%	100.0%
	Mean Error	-0	-11.6	-24.9	-38	-12.1

Figure 7 Comparison of assigned geological strength index (GSI) (50th percentile) values in geotechnical units inside the poor-quality zone model with cell mapping. In the graph, each row corresponds to a geotechnical unit

4 Performance of geotechnical approaches in stability analyses: a case study

The three approaches described above (block models, homogeneous geotechnical units and the PQZM) have been employed in stability analyses for the mine during various assessment cycles. These stability assessments have included analyses encompassing a wide range of methods, including empirical, analytical, stochastic and numerical.

In terms of numerical stability analyses, both 2D and 3D types have been carried out during these assessment cycles. However, the most prominent – due to its relevance to the mine plan, as well as its level of complexity and representativeness of the pit – is the analysis conducted using the distinct element method through 3DEC software (ITASCA 2024). Its use is justified by the tool's capability to represent a large number of structural features explicitly, which is essential in a structurally controlled environment such as this mine.

As is customary to establish a good degree of reliability in the predictive stages derived from a numerical model, calibration exercises have been performed. In most of them the aim was replicating a failure mechanism of significance to the mine.

Considering the several calibration models carried out throughout the various analysis cycles conducted, where sensitivity analyses have included geotechnical parameters such as intact rock strength, fault strength, disturbance factor and groundwater conditions, it has been concluded that the variable with the greatest uncertainty is the GSI. As shown both in Section 2 and Section 3, focus has been drawn to the GSI due to the discrepancies observed between the field-mapped GSI values and the those predicted by block models.

In one of the calibration stages, one of the most historically relevant instabilities for the mine was considered. This major-scale instability corresponds to a failure mechanism strongly influenced by two major faults. One extends throughout nearly the entire pit (Fault 1), and the other is located on the southern wall and extending approximately 900 m (Fault 2). These major faults have altered the surrounding rock through intense argillic alteration, resulting in rock masses of poor to very poor geotechnical quality. This setting is hosted within a rock mass of fair to poor geotechnical quality and is further influenced by the presence of an oblique planar minor structural set. The failure mechanism developed progressively with the excavation of the slope, ultimately reaching a vertical extent of 350 m. Figure 8 shows a view of the wall of the pit, highlighting the instability.

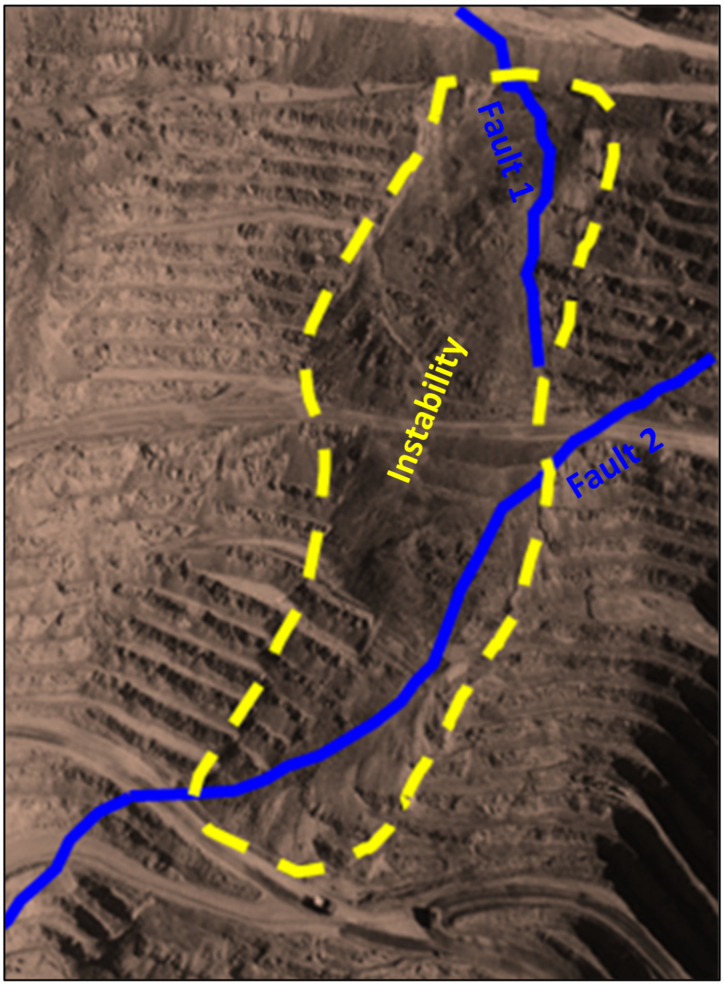


Figure 8 Major-scale instability at the pit wall

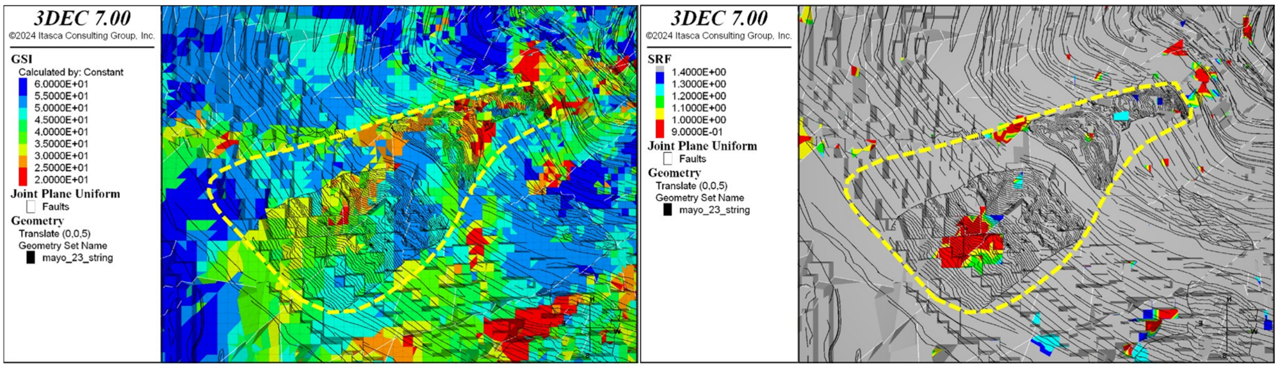
The following presents results of the performance of each geotechnical characterisation approach in terms of GSI for the numerical analysis involving calibration of the instability, showing its evolution over time (Sections 4.1 to 4.3). For evaluation purposes, strength reduction factor (SRF) contours are used, obtained through the shear strength reduction technique (Dawson et al. 1999). Values of 1.0 or lower are considered unstable areas, while values between 1.1 and 1.2 are regarded as quasi-stable.

4.1 Block model approach

The first approach to replicating the instability considered the GSI block model valid at the time of the analysis. However, as mentioned in Section 2, when compared with field mapping data this block model generally overestimates the rock mass quality, which is a critical factor when attempting to reproduce geotechnically significant areas.

Figure 9a presents the GSI distribution provided by the block model for the instability area (outlined in yellow), while Figure 9b shows the SRF values for the same sector.

It is evident that when using this input for the numerical model the mechanism did not match the scale expected because the mobilised zone is significantly smaller than the actual extent observed in the field. In this regard the calibration was not considered satisfactory; consequently, further adjustments and assumptions were required, which in turn weakened the credibility of downstream analyses.



(a) (b)

Figure 9 Block model approach. (a) Geological strength index (GSI) contour; (b) Strength reduction factor (SRF) contour

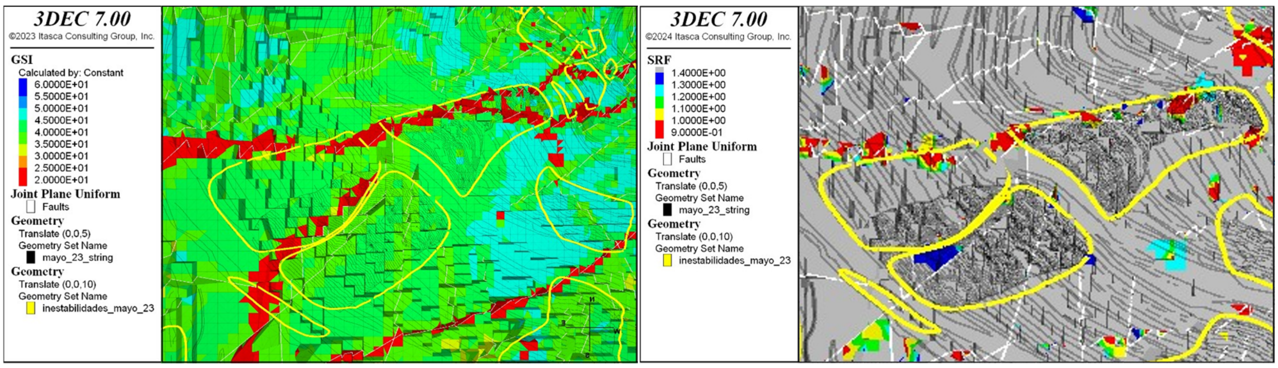
4.2 Homogeneous geotechnical units approach

A second approach considered a GSI distribution under the assumption that each geotechnical unit is spatially homogeneous and assigned a single value per unit. In this case, comparison with field data indicates that this approach under-represents areas with GSI values below 30 while over-representing sectors with GSI values above 30. This was illustrated in Figure 2.

Additionally, the numerical model included the assumption of a continuous alteration halo along the entire extent of each major fault (defined as geological structures with an extent greater than 300 m), reducing the geotechnical quality of the rock mass within this halo. Although this is a conservative calibration adjustment it is based on field data, where surface mapping has recorded alteration zones around faults, but not to the full extent assumed for the numerical analysis.

Figure 10a presents the GSI distribution by assuming each geotechnical unit is spatially homogeneous, assigning a single value per unit for the instability area (outlined in yellow), whereas Figure 10b shows the SRF values for the same sector.

In this case it can be observed that in the area where the instability would be expected to manifest, only a continuous lineament of unstable SRF values appears, following the Fault 1 zone. This indicated that the calibration was also not considered satisfactory, requiring further adjustments and assumptions that weaken the reliability of downstream analyses.



(a) (b)

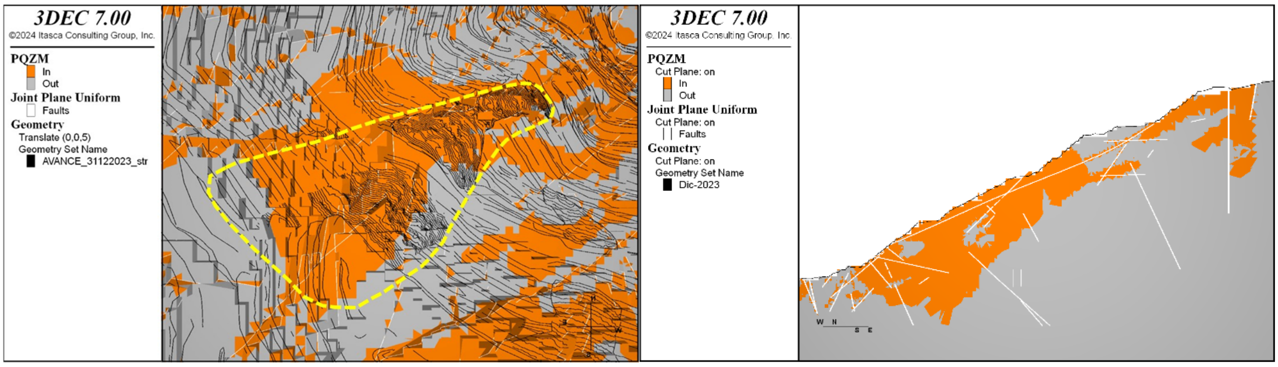
Figure 10 Homogeneous geotechnical units approach. (a) Geological strength index (GSI) contour; (b) Strength reduction factor (SRF) contour

4.3 Poor-quality zone model approach

Finally, for the most recent cycle of stability assessments, the geotechnical characterisation approach based on the PQZM was used. Under this approach, representative GSI values are assigned both inside and outside the PQZM for each geotechnical unit. Figure 11 shows the application of the PQZM for the instability area (outlined in yellow), while Figure 12a exhibits the GSI distribution obtained and Figure 12b presents the SRF values for the same sector.

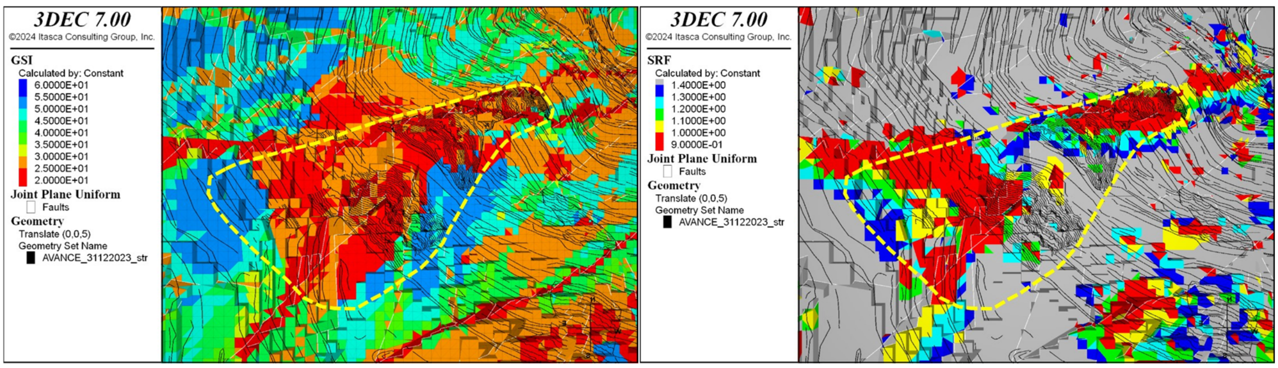
In this case a clear distinction can be observed between zones classified as having poor geotechnical quality (GSI values below 30) and those classified as fair to good quality. At the same time, it is evident that most of the rock mass within the instability contour corresponds to poor-quality rock. In this context, when reviewing the results of the calibration exercise, areas with SRF values consistent with the development of the instability can be seen, achieving a higher level of representativeness and consequently resulting in a satisfactory calibration.

Although a reasonably good calibration is expected in each cycle of stability analysis it is often achieved based on assumptions and considerations that must be discussed and agreed upon using the information available at the time of the assessment. This indirectly leads to reduced reliability in predictive scenarios, requiring additional studies to compensate for this weakness. In this regard, the use of approaches such as the PQZM has helped not only to address both these assumptions and considerations but also to enhance the reliability of stability assessments as it is a tool derived from the direct analysis of site-specific geological information which is continuously updated to improve its representativeness.



(a) (b)

Figure 11 Poor-quality zone model (PQZM) assignment. (a) Top view; (b) Section view on instability



(a) (b)

Figure 12 Poor-quality zone model approach. (a) Geological strength index (GSI) contour; (b) Strength reduction factor (SRF) contour

5 Discussion and analysis of results

Thanks to the exercise carried out it was established that different geotechnical characterisation approaches – in this case focused on the GSI parameter, with no changes on the rest of the geotechnical parameters – when used as input for the same stability analysis in the pit, produced different results. While this is to be expected in any type of modelling, it is particularly critical in models aimed at assessing geotechnical stability, where outcomes often have a direct impact on safety, planning and project value.

In this context, areas of the rock mass classified as poor to very poor quality are of particular interest in geotechnical studies due to their significant role in stability. Depending on the level of available information, these areas are often under- or over-represented in geotechnical characterisation models, negatively affecting the reliability of the model response and influencing decisions across other parts of the process.

As previously stated, these gaps between what is shown by the geotechnical characterisation and the response obtained from stability models are commonly addressed through assumptions and considerations during calibration stages. While these may achieve the desired outcome (i.e. the SRF of a past phenomenon), they indirectly reduce the reliability of downstream analysis stages, particularly predictive scenarios.

In this regard the calibration of models involves an iterative process in which common parameters are adjusted, assumptions are made and new considerations are introduced – as previously discussed and based on the information available at the time of the study.

This process is often not immediate. It may take several weeks and is widely understood to strictly represent current conditions, and perhaps immediate future scenarios (one or two years, depending on the assumptions), but it lacks validity in the long-term.

This reduction in the reliability of predictive scenarios is commonly addressed through sensitivity analyses within the models, which in most cases result in responses that are quite or excessively conservative compared to the actual site conditions.

A sound geotechnical characterisation based (as far as possible) on all available field data and involving continuous updating not only has a positive impact on the outcomes of downstream assessments, such as the numerical stability models discussed, but also enhances the overall reliability of the site's geological information.

This in turn leads to greater representativeness and credibility while reducing uncertainty in any process where this information is used as input. As a result, the need for adjustments, assumptions and external considerations that may distort the process is minimised. The outcome, in terms of geotechnical stability, is a response that is not necessarily conservative but rather well aligned with the current site conditions and supported by a higher degree of information reliability.

Considering the specific case of the mine, and as previously illustrated in terms of GSI, the approach to its geotechnical characterisation has evolved over time, giving rise to new methodologies that have positively impacted subsequent processes and studies. Approaches such as the PQZM have significantly improved the representativeness and reliability of the available geological information, indirectly reducing the reliance on assumptions and additional considerations.

In terms of stability results, using the calibration of a historical instability through numerical modelling as a point of comparison, the PQZM approach clearly demonstrates better performance when compared to other methods. Given that the rock mass qualities found in the pit are at best fair, the ability to specifically model poor to very poor-quality rock masses is significantly improved under this approach.

This allows for a cleaner representation of pit conditions for both current and retrospective scenarios; thereby enabling calibration without the need for additional adjustments or assumptions while also resulting in greater confidence in the prediction of properties and future scenarios.

The PQZM approach is particularly useful in a rock mass such as that of the mine, as the main historical instabilities are associated with areas of high fracturing and alteration, i.e. poor-quality rock. In this context, to replicate the workflow used with this approach and potentially apply it to other settings, it is recommended that the following be considered:

- Progressively improving the reliability of geotechnical parameters: this involves continuously evaluating the subdivision of geotechnical units with high variability and isolating poor-quality rock masses to enable more accurate characterisation
- Enriching the database with additional information: this means conducting targeted geotechnical drilling campaigns in areas with low data density. At the same time, a greater number of rock samples should be tested in geotechnical units (or potential units) that currently lack adequate representation
- Reviewing the assumptions and considerations used in previous analyses: this includes identifying potential under- or over-representations of poor-quality zones, comparing them with field data, and continuously feeding back and updating the PQZM accordingly.

6 Conclusion

As previously mentioned, the representativeness and prediction of rock mass areas with poor to very poor quality in characterisation models is of geotechnical interest. These areas generally play a significant role in the outcomes of several assessments, such as the stability analyses illustrated earlier, often influencing responses in terms of safety, planning and impacting the value of projects.

Various approaches have been employed at the mine over the years to enhance its geotechnical characterisation, consistently aiming to improve site representation, increase the reliability of geotechnical models and reduce associated uncertainty. Using the GSI parameter as a case study, approaches such as the PQZM method have enabled the definition of a poor-quality rock domain, which is well-suited to the predominant rock mass type. This has provided a higher level of confidence in the prediction of geotechnically significant areas, thereby reducing uncertainty in the analysis of future scenarios.

Specifically for 3D numerical modelling stability analyses, such as those illustrated in this study, this approach has shown better performance at the mine compared to assuming homogeneous geotechnical units or using a geological strength index block model alone when conducting calibration exercises and evaluating predictive stages. In this context, a major advantage of this approach is that it avoids the need for excessive adjustments, assumptions or considerations to validate the reproduction of historical phenomena such as the instabilities observed in the pit.

Nevertheless, the level of confidence in the PQZM will always depend on the geological and geotechnical database available at the time of the assessments. Therefore, it must be continuously updated and refined with new field information. In this regard, subsequent studies should also be regularly reviewed, as needed, in order to provide more accurate responses based on more representative and reliable data.

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