**Quantifying the influence of drilling additional boreholes on
the quality of a geological model**

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Quantifying the influence of drilling additional boreholes on the quality of a geological model

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Abstract

Geotechnical stability analysis in open pit mines requires access to a representative geotechnical model. The confidence level in the collected geotechnical data influences slope design. This paper investigates the influence of the number of boreholes, drilled to collect geological information, on the quality of one component of the geotechnical model, the geological model. The number of boreholes influences the number of rock core samples collected for the identification of rock type, the definition of geotechnical domains and their boundaries within the rock mass. A challenge in the definition of the geotechnical domains is the determination of the drill hole density that minimizes the variation in the interpreted geological model from the actual rock mass.

In order to quantify the influence of the drill hole density, boreholes are simulated in the most recently updated geological model for three mine sites. The simulated drill hole density increased progressively until the variation of the interpreted section, compared to the original section, is minimised. A classification strategy was developed to determine the complexity level for each geotechnical domain. Furthermore, a series of empirical quantitative guidelines are presented prescribing the minimum drill hole density per domain complexity, while limiting variations from the actual rock mass.

Keywords

Geological model, drill hole density, confidence level, geotechnical domain complexity, geological data collection

1. Introduction

In an open-pit mine operation, the design of safe and economically viable slopes requires a representative geotechnical model. It is recognized that the geological model is one of the components of the geotechnical model that is generally used for the definition of the geotechnical domains. The quantity and quality of the geotechnical data collected influences the quality of the corresponding geotechnical model. In several mining jurisdictions, codes and standards are available for reporting exploration data (JORC 2012, CIM 2003, etc.), but similar codes or guidelines are not readily available or require compliance for geotechnical mine design. This suggests that the level of confidence in geotechnical design data is potentially less than for the data used for resource and reserve estimation (Hadjigeorgiou 2012; Haile 2004; Read 2009; Steffen 1997). A strong case has been made by Terbrugge et al. (2009) and Steffen (2014) for the use of confidence categories in the data for slope design. Existing guidelines for open pit slope design recognise that the geotechnical data are collected throughout the timeline of a mine operation, and that the level of confidence in the collected data should, in theory, increase from the early conceptual stage to the more mature stages of a mining project (Read and Stacey 2009). Given that existing guidelines are qualitative, it is not evident what quantity of data has to be collected in order to reach the targeted levels of confidence.

This paper investigates the influence of the drill hole density on the resulting interpretation of the geological model. Increasing the drill hole density can result in an increased confidence level in the 3D geological model used for delineating or zoning of the geotechnical domains in a mine. The number of drilled boreholes influences the number of rock core samples collected for the identification of the rock types and consequently, the definition of the geotechnical domains and their boundaries within the rock mass. A practical challenge in the definition of the geotechnical domains is to determine how many boreholes are required to minimize the difference between the interpreted geological model and the actual rock mass. This will facilitate the collection of the data quantity that will result in a sufficient level of confidence in the geological model.

The ISRM recommendations on site investigation techniques (ISRM 1975) specify that the number of borings depends on the geological homogeneity of the area to be investigated. The more irregular the area, the more drilling is necessary (reduction of the drill spacing) to define areas of homogeneity. There are currently no quantification guidelines for the number of boreholes necessary to define areas of homogeneity. Furthermore, the defined

geotechnical domains may not be homogenous. For example, the geotechnical domains may comprise a variety of rock types that have encountered different degrees of deformation. The number of boreholes may then depend on the geological and structural complexity level of the geotechnical domains encountered on site.

An approach to quantify how the geological information density influences the resulting geological model was suggested by Scoble and Moss (1994). This consisted by a study of geological sections mapped in detail from old cut and fill stopes at Inco's Thompson Mine. The purpose of the study was to evaluate the accuracy of ore location and its relation to dilution in a vertical section. Ore dilution is due to waste material (i.e. material with no economic value) that is not separated from the ore (i.e. rock or mineral with an economic value) during mining and subsequently processed. Artificial drill intersections (i.e. location of the ore intersections obtained from simulated boreholes) over a range of 34, 17, and 8.5 m vertical spacing were constructed on the sections and given to mine geologists to interpret ore outlines. These were then given to mine engineers to establish mining lines and to estimate unplanned dilution. Figure 1 shows the vertical sections obtained from different drill hole densities (i.e. 100 foot, 50 foot and 25 foot information interpretation). The results showed that the interpreted sections converge to the actual geological section as the drill hole density increases and that ore loss (i.e. ore that is not mined or considered as waste material) and planned dilution may vary according to information density.

In this investigation a similar approach to Scoble and Moss (1994) was used to provide a better understanding of the effect of the number of boreholes on the interpreted geological model. Hypothetical boreholes were simulated in the most recent available versions of the geological models for three mines. The mines in this study, were selected based on the good quality of their geotechnical database and geological models. This implies that the mines applied best practice guidelines for the geotechnical data collection. The simulated drill hole density was progressively increased to determine the drill hole density that minimizes the variation of the interpreted section compared to the original section. A classification system for determining the geotechnical domain complexity level (geological and structural complexity) was developed to provide empirical quantitative guidelines with respect to the minimum drill hole density per domain complexity for a minimum variation from the real rock mass.

2. Case studies

The investigation on the role and influence of the drill hole density on the definition of the geological model was based on three operating mines. For this purpose, three open pit mines were selected based on the quality of the

available data. The first step of the investigation was to conduct a comprehensive review and validation of the geotechnical database available at the three mine sites. The three mining operations that provided access to their mines and geotechnical databases are located in South Africa and are operated by Anglo American, an international mining company with a wide variety of mines in the operations stage. In this paper, the three mines are referred as Mine A (diamond mine), Mine B (diamond mine) and Mine C (iron mine). A summary of the geotechnical domains included in the mines' 3D geological models is presented in Section 2.1 to 2.3.

2.1. Mine A

Mine A is a diamond bearing kimberlite pipe resource. The most recent available version of the geological model (i.e. a 2012 version), including 13 different geotechnical domains, is presented in Figure 2. Mine A is located in the Karoo basin, a large sedimentary basin of Phanerozoic age. The upper Volksrust formation (VO) consists of deep-water fine grained sediments characterised as massive carbonaceous rich mudrock with very few internal structures. The lower Vryheid (VR) formation comprises a wide range of sediments ranging from mudrock to siltstone, sandstone to conglomerate. The Vryheid comprises both aerial and sub-aerial deltaic environments (VRM, VRSSC, and VRVS). During the Jurassic, crustal extension in southern Africa resulted in a number of dolerite dyke swarms (DOL). The Kimberlite intrusion (KIM) also occurred in the Jurassic – Cretaceous boundary (I. J. Basson and D. Tennant, personal communication, July 2012).

2.2. Mine B

Mine B ore bodies consist of diamondiferous kimberlite pipes. The country rock at Mine B consists mainly of metamorphic and intrusive igneous rocks and is part of the Limpopo Belt. The rock in the immediate vicinity does not have a clearly defined stratigraphy and is part of the highly deformed Beit Bridge Complex. This Complex can be divided into the Malala Drift and Gumbu Groups. Those groups were further sub-divided into the following packages (W. P. Barnett 2007, personal communication, November 2007):

- The Gneiss Package (GP) which comprises predominantly biotite gneiss, biotite schist, quartzo-feldspathic gneiss and amphibolitic gneiss from the Malala Drift Group.
- The Metasedimentary Package (MP) which comprises metacarbonate interbedded with metapelite, metapsammite and micaceous quartzites from the Gumbu Group.

- The Marble Suit (MBL) from the Gumbu Group.
- The kimberlites (KM) pipes and dolerite dykes and sills (DOL) are cross-cutting the previous packages.

The main geotechnical domains expected in the country rock at Mine B (i.e. excluding the kimberlite domain) in the most recent version of the geological model (i.e. 2012 version) are summarised and graphically illustrated in Figure 3.

2.3. Mine C

The ore bodies at Mine C consist of banded iron formations (BIF). The country rock stratigraphic column at Mine C (Figure 4) is resulting from a fault-controlled sub-basin. Carbonate and dolomite (DOL) are present at the base and a siliceous Chert breccia (CH) overlies dolomite. The formation grades upwards into banded ironstone (BIF), occasionally interlayered with shales. The upper part comprises a series of ore horizons (ORE) which are interlayered with BIF and shale.

An unconformity, due to erosion and probable uplift, is present between the Iron Formation and the Gamagara Formation (GAM). Gritty or conglomeratic ore overlies the unconformity. The GAM Formation also contains numerous shale horizons. Flagstone (FLS) overlies the variably eroded lower Gamagara. Above FLS, quartzite (QTZ) is underlain by a thin, tectonized shale horizon (SHTL) and a very irregular upper tectonized shale (SHTU) is directly overlying quartzite.

Above the upper tectonized shale, the “lava” (LAV) and “weathered lava” (LAW) are encountered and represent andesite or andesitic volcanics with different geotechnical properties. Tillite (TIL) is distinct from andesitic lavas or andesites. Highly irregular pebble unit (PEB) and sandstone unit (SD) are overlying andesite. Above the pebble layer, a thick clay layer (CLAY) is encountered. This clay layer is overlain by a thick calcrete layer (CC).

Diabase dykes (DIA) are present at Mine C and the primarily intruded DOL, CH, BIF, ORE and GAM. Dykes occur mainly along major N-S trending partially inverted normal faults that typically show downthrows to the west. Dykes partially intruded into QTZ and terminated below the andesite (LAV/LAW) (D. Tennant and I. J. Basson, personal communication, November 2013).

The main geotechnical domains anticipated in the country rock at Mine C, in the most recent version of the geological model (i.e. 2013 version), are summarised and illustrated in Figure 4.

3. Method of analysis

In order to investigate what constitutes a sufficient number of boreholes to define the geological model, an approach similar to Scoble and Moss (1994) was used. Boreholes were simulated in the geological models of the case studies (Mine A, Mine B and Mine C) to quantify the variation of the interpreted section from the original section for different drill hole densities. The simulated boreholes are not physical boreholes. Hypothetical boreholes were used to be able to analyse a variety of drilling strategies (i.e. drill hole densities) and quantify the influence of the different scenarios on the interpretation of the corresponding geological model. For each case study, the drill hole density (i.e. the number of simulated boreholes in the 2D section) was progressively increased to determine the number of boreholes required to minimize the variation between the interpreted section and the original model. The original section is the geological section obtained from the most up-to-date geological model at the mine site which was assumed to be the most representative. It is recognised that as mining advances and more exposures are available, it is possible to continuously update the geological model.

Deviations in the interpreted sections, for different drill hole densities, were quantified based on the percentage of variation. The geotechnical domain areas on the original section provided the reference point or benchmark. The percentage of variation was calculated by considering the corresponding domain areas in the various interpreted sections. The percentage of variation of the interpreted section from the original section was then calculated with Equation 1:

$$Variation (\%) = \left| \frac{Area_{interpreted} - Area_{original}}{Area_{original}} \right| \times 100 \quad (1)$$

This process allowed the determination of the drill hole density required to adequately define the geological model. The up-to-date case studies models (2014 models) were used to represent the original section and were assumed to be representatives of the reality.

The GEMS software package (Dassault Systemes 2015) was used for geological modelling, boreholes simulation and interpretation of the geological sections. The 2D sections were interpreted by a mining engineer, reviewed by the authors and an independent geologist. It should be noted that only the final reviewed sections were used for the analyses (i.e. one section per simulated drill hole density for each case study). 2D sections were used instead of 3D

volumes because for geological modelling using GEMS, a 2D section is first interpreted and used subsequently to model the 3D volumes. The 2D sections are then the input data to the geological model and their interpretation has a direct effect on the resulting 3D geological model. It is important to have a sufficient level of confidence in the 2D sections before taking the next step, i.e. before interpreting the 3D volumes from the different 2D sections analysed.

Figure 5 is an example of the different steps undertaken for the analyses for Mine A. For this particular case study example, the kimberlite pipe was assumed to be previously known from the resources and reserves definition. The different steps of the analysis consist of simulating hypothetical boreholes in the 3D geological model, preparing 2D sections, updating the boreholes intervals based on the intersections with the original model, interpreting the 2D sections based on the simulated boreholes, comparing the geotechnical domains areas with the original section and finally, calculating the variation of the interpreted section from the original geological model.

The analysed sections and the drill hole densities are presented in Table 1 for the three different mine case studies.

- For Mine A, the W – E section was analysed with vertical boreholes and drill hole densities from 1 borehole every 550m (i.e. 2 boreholes on the 2D section) to 1 borehole every 125m (i.e. 13 boreholes on the 2D section).
- For Mine B, the W – E section was analysed with vertical boreholes and drill hole densities from 1 borehole every 890m (i.e. 3 boreholes on the 2D section) to 1 borehole every 125m (i.e. 22 boreholes on the 2D section).
- For Mine C, the E – W section was analysed with vertical boreholes for Sector 1, Sector 2 and Sector 3 with drill hole densities from 1 borehole every 900m (i.e. 3 boreholes on the 2D section) to 1 borehole every 150m (i.e. 18 to 20 boreholes on the 2D section). For Mine C, the E – W section in Sector 2 was also analysed with 50° inclined boreholes and the same drill hole densities.

4. Results of the interpreted sections vs the original model per drill hole density

The calculated percentage of variation of the interpreted sections, from the original model for different drill hole densities, are presented in sections 4.1 to 4.3 for Mine A, Mine B and Mine C respectively. A summary of the results of the three case studies is presented in section 4.4.

The interpreted sections presented in sections 4.1 to 4.3 are different for each analysed drill hole density because the delineation of the geotechnical domains is influenced by the number of borehole intersections within the geotechnical domains and the location of those intersections. In practice, as the number of simulated boreholes increases, more intersections within the various geotechnical domains become available to the interpreter to establish the boundaries of those domains. The probability to intercept significant changes in the geotechnical domains boundaries is also higher as the number of boreholes increases. The smaller the spacing between the simulated boreholes, the less significant is the influence of the borehole location in the delineation of the geotechnical domains. This explains the generally higher variation in the geotechnical domains boundaries on the interpreted sections for small drill hole densities.

For each mine site, the interpretation based on the simulated geotechnical drill hole densities, assumed that no information was previously available for identifying the geotechnical domains. This implies that each simulated drill hole density is independent of the other analysed drill hole densities. Quite often, when the drill hole density is increased, and additional geological data are collected, the interpretation of the geological sections is based on the geology identified from the previous boreholes and on the information collected with the new boreholes. In this case, the variation of the interpreted section from the actual rock mass is likely to decrease as the drill hole density increases. For this investigation, each drill hole density represented a new drilling campaign and not an update of the geological model. Significant changes in the percentage of variation of the interpreted section from the original model were observed (i.e. a significant increase or decrease of the % variation) for some geotechnical domains as the drill hole density increases. This was particularly significant for smaller drill hole densities. Those changes in the percentage of variation are also more significant for the smaller geotechnical domains (i.e. domains with less continuity within the rock mass) because, for smaller drill hole densities, the probability to intercept smaller domains is lower. Contrary to the larger domains, the delineation of the domains is highly affected by the location of the sampling boreholes.

4.1. Mine A

At the time of the investigation, the geological model at Mine A was developed from a total of 153 boreholes (drilled between 1966 to 2013), including 46 geotechnical boreholes. This model was used to establish the original section for the analyses. The kimberlite pipe area was assumed to be known from the resources and reserves

definition. The domains area were calculated for the 9 country rock geotechnical domains, i.e. VO_RIP, VO_CONS, VRM_RIP, VRM_CONS, VRSSC_UP, VRSSC_LOW, VRVS, DIAM and DOL. Note that the DIAM geotechnical domain was not crossed on the W – E section analysed. Figure 6 shows an example of three interpreted sections for different drill hole densities for Mine A. Figure 7 shows the percentage of variation of the interpreted section from the original model for the different drill hole densities. As shown in Figure 7, the variation is smaller than 10% for all geotechnical domains for a drill hole density higher or equal to 1 borehole every 175m.

4.2. Mine B

At the time of the investigation, the geological model at Mine B was developed from a total of 917 boreholes (from 1981 to 2009), including 149 geotechnical boreholes. This model was used to establish the original section for the analyses. The kimberlite pipes areas were assumed to be known from the resources and reserves definition. The domain areas were calculated for the 4 country rock geotechnical domains, i.e. DOL, GNEISS, METASED and MBL. Figure 8 shows an example of three interpreted sections for different drill hole densities for Mine B. Figure 9 illustrates the percentage of variation of the interpreted section from the original model for the different drill hole densities. As shown in Figure 9, the variation is smaller than 10% for all geotechnical domains for a drill hole density higher or equal to 1 borehole every 230m.

4.3. Mine C

At the time of the investigation, the geological model at Mine C was constructed based on data from 14,588 boreholes (drilled from 1948 to 2014), including 203 geotechnical boreholes. This model was used to establish the original section for the analyses. The domains area were calculated for 14 geotechnical domains, including the ore deposit (i.e. CLAY, CC, PEB, LAV, LAW, SHTU, QTZ, SHTL, FLS, GAM, ORE, BIF, CH, and DOL). The analyses were performed by simulating vertical boreholes for Mine C Sector 1, Sector 2 and Sector 3 pit sections. Figure 10 shows an example of two interpreted sections in Sector 1 for different drill hole densities. For Sector 2, the analyses were also performed with inclined boreholes and an example for two interpreted sections is presented in Figure 11. Figure 12 to Figure 15 show the percentage of variation of the interpreted section from the original model for the different drill hole densities for Sector 1, Sector 2 (with vertical and inclined boreholes) and Sector 3 respectively. As illustrated in Figure 12 to Figure 15, the variation is smaller than 10% for most geotechnical domains for a drill hole density higher or equal to 1 borehole every 150-200m.

4.4. Summary of the results for the three case studies

The results of the three case studies, comprising a total of 27 different geotechnical domains, show a similar trend with respect to the variation of the interpreted section from the original section. Table 2 shows the minimum drill hole density for which the variation of the interpreted section from the original section is less than 10%. Based on the results from this empirical approach, a preliminary drill hole density of 1 borehole every 175-250 meters is suggested to minimize the variation of the interpreted geological model from the real rock mass.

There are some limitations in the undertaken analyses. In the first place, the interpreted model can vary with the site stratigraphy and the borehole inclination. In effect, there is a greater probability to intercept horizontal domains (e.g. sedimentary rocks) with vertical boreholes and consequently, to intercept sub-vertical domains (e.g. dyke and diabase) with inclined boreholes. The interpretation can vary from one person to another because the extrapolation of the domain boundaries, between the intersections identified in the boreholes, is subjective as it depends on the interpreter's intuition and experience. This has highlighted the need for a better guidance in the planning of geological data collection campaigns performed to define the geotechnical domains and used subsequently for slope design.

The preliminary drill hole density of 1 borehole every 175-250 meters was proposed based on the results of the five different sections analysed. It implies that using a higher drill hole density should not have a significant effect on the interpreted section for the entire site which comprises a variety of heterogeneous domains. As shown in Table 2, the variation of the interpreted section from the real rock mass would not be greater than 10% for most domains, even if it is decided to drill additional boreholes. It is recognized that, for homogeneous domains, the required drill hole density may be significantly smaller and this aspect is further investigated in Section 5.

5. Developed guidelines for selecting the drill hole density

As suggested in the ISRM recommendations on site investigation techniques (ISRM 1975), the number of boreholes depends on the homogeneity of the area to be investigated geologically. This implies that there is an optimal drill hole density which varies with the geotechnical domain complexity (geological and structural complexity). In the process of developing guidelines for selecting the optimal drill hole density, the domain complexity must be defined. Furthermore, because the optimal drill hole density may also depend on the level of information required for the

purposes of the work to be performed, the anticipated percentage of variation of the interpreted model vs. the real rock mass should also be considered.

Section 5.1 presents the classification system developed to define the domain complexity. The performed analyses, per domain complexity, are presented in Section 5.2. Finally, the proposed guidelines for selecting the drill hole density are discussed in Section 5.3.

5.1. Classification system for the domain complexity

Arguably, the drill hole density will vary based on the ground or geological conditions. A classification system was developed by the authors to define the domain complexity. The classification system is based on the geotechnical domain homogeneity and on the geological and structural complexity of the rock types in the domain with the input of the available data of the three mine case studies. The developed classification system suggests three levels of domain complexity, i.e. low, medium and high complexity. The complexity level of the different domains was also assigned based on a review of structural and geological data with the input of a geologist and on the work of Higgins (1971) as presented by Steffen (2014). A statistical analysis was undertaken on the results of laboratory tests capturing the mechanical properties of rock types representative of the geotechnical domains identified at the mine sites. The analysis included the determination of the data distribution, the data range, the sample average, the standard deviation, the coefficient of variation and the confidence level based on a predetermined precision index. For indicative purposes, an example of the statistical analysis conducted is presented in Fillion and Hadjigeorgiou (2017) for uniaxial compressive strength data at Mine A. For each geotechnical domain, the mechanical properties were obtained through a series of laboratory tests (uniaxial compressive strength, density, tensile strength, elastic modulus and Poisson's ratio). The variability of the mechanical properties was determined, resulting in a better understanding of the geotechnical domain complexity. This approach contributed to further fine-tuning and refining of the classification system. The developed classification system is presented in Table 3.

The developed classification system suggests that the complexity level can be determined based on a series of criteria. It is recognised that these criteria are subjective and are provided to aid the designer in assessing the complexity levels of the geotechnical domains of a particular mine site.

- The rock type (i.e. igneous, sedimentary and metamorphic) provides an indication of the geological complexity. In general, igneous rocks are more homogenous than sedimentary and metamorphic rocks,

within a typical area in an open pit mine project. This is a consequence of the formation processes which are usually more variable for sedimentary and metamorphic rocks.

- The number of rock types, included in a particular geotechnical domain, is another criterion for assessing the domain complexity level. Domains comprised of only one rock type are generally less variable than multiple rock type domains.
- For metamorphic rocks, the complexity level may also depend on the intensity of the deformation (contact, regional or dynamic metamorphism), the metamorphic facies (e.g. the conditions of pressure and temperature during formation) and the presence of tectonic fabrics (e.g. lineation, foliation).
- Finally, the degree of weathering is another criterion to consider as the properties of weathered rocks are generally more variable than fresh rocks.

In the classification system, a low complexity domain consists of a homogeneous rock mass with one rock type. Most granitic and plutonic rocks may fall in the low domain complexity category. A medium complexity domain consists of 2-3 rock types of different competencies. Faults may be present in the domain but the rock mass would not have encountered crustal plate movement. Most sedimentary rocks would be in the medium complexity category as well as different types of intrusions and some metamorphic rocks. Finally, a high complexity domain consists of multiple rock types in tectonically affected areas. This domain may be located in a shear zone, or in areas with intense deformation and/or folding. Many metamorphic rocks may fall in the high complexity category as well as highly weathered sedimentary rocks. Note that the rock type examples given in Table 3 are for indicative purposes only. The complexity category should be assigned based on the observed site-specific variability. This requires an element of judgement from the geotechnical engineers and can benefit from the input of experienced site geologists to minimize the subjectivity of the suggested classification system.

5.2. Variation of the drill hole density vs. the domain complexity

During the lifetime of an open pit mine operation, the geological model is further refined from the early stages of a project to the more mature stages of an operating mine. It is recognised that the level of confidence required at the early conceptual stage is generally smaller than for the late operations stage. The number of boreholes (i.e. drill hole density) required to adequately define the geological model should also increase from the early stages to the more mature stages.

In an effort to address the geotechnical data uncertainty, a qualitative template has been proposed by Read and Stacey (2009). A series of qualitative guidelines have been suggested to identify the required level of geotechnical effort and target levels of data confidence as a function of the stages in a mining open pit project (conceptual, pre-feasibility, feasibility, design & construction and operations). These guidelines proposed different targeted level of confidence for the subcomponents of the geotechnical model, such as the geological, rock mass, structural and hydrogeological models. The suggested levels of confidence and the corresponding level of effort in data collection for the geological model are presented in Table 4. The presented reporting system that defines levels of confidence in the data used to build the geological model is qualitative and there is no quantification process regarding the number of boreholes (drill hole density) required to reach the targeted levels of confidence. This is an important limitation.

In an attempt to provide quantitative guidelines for the required drill hole density, the results from the three cases studies are used to suggest a drill hole density per domain complexity for an anticipated maximum variation from the real model. The percentages of variation are related to the confidence levels for the geological model suggested in Read and Stacey (2009):

- Conceptual stage: $\leq 50\%$ variation
- Pre-Feasibility stage: 30 – 50 % variation
- Feasibility stage: 15 – 35 % variation
- Design & Construction stage: 10 – 20 % variation
- Operations stage: $\leq 10\%$ variation

It is recognised that the number of boreholes required to identify the geotechnical domains and their boundaries within the rock mass depends on the geological and structural complexity of the rock types included in the domain. To determine the number of boreholes required for an anticipated maximum variation from the real rock mass, it was first necessary to assess the level of complexity of the geotechnical domains identified at the mine sites. Table 3 was used to assign a complexity level to the 27 geotechnical domains of the three mine case studies. The percentage of variation of the interpreted section from the original model, for different drill hole densities are presented in Figure 16 a, b and c for the domains with low, medium and high complexity. As shown in Figure 16, the variation is generally higher when the complexity level of the domains is higher. The dashed lines in Figure 16 correspond to

the suggested variation limits for the different project stages. The minimum drill hole density that respects the variation limits was selected based on the most variable domain for each complexity level. The results of the analyses, performed per domain complexity, were used to develop the guidelines for the suggested number of boreholes required to adequately define the geological model. The guidelines are presented in Section 5.3.

5.3. Guidelines for selecting the drill hole density

Based on the previous analyses, a series of empirical guidelines has been developed to suggest a minimum drill hole density that could minimize the variation of the interpreted geological model from the real rock mass. The guidelines, presented in Table 5, are based on the level of details required (i.e. the maximum acceptable variation of the interpreted model from the real rock mass) and on the complexity level of the geotechnical domains. The suggested guidelines were based on three case studies with a total of 27 geotechnical domains of different levels of complexity (i.e. different rock types, formation environments and structural characteristics). As shown in Table 5, the required drill hole density increases from the early Conceptual stage to the advanced Operations stage, and from the low complexity level to the high complexity level. The suggested drill hole densities are per geotechnical domain, i.e. for the same site, the drill hole density should be increased in areas where higher complexity domains are intersected. For indicative purposes, for a 2 km² site, a drill hole density of 1 hole every 900m represents 5 boreholes and a drill hole density of 1 hole every 125m consists of 256 boreholes.

Note that the guidelines presented in Table 5 use the same project stages as defined in the guidelines for open pit slope design (Read and Stacey 2009). The guidelines could also be used for a variety of projects in engineering geology depending on the level of details required (i.e. the maximum variation acceptable) for the project under considerations.

6. Discussion

The selected mine sites had a comprehensive database and the geological model were regularly updated with additional information. It was assumed that the most up-to-date geological model was representative of the rock mass. The most up-to-date geological model is still interpolated from the domains identified in boreholes which constitutes a limitation of this approach. Nevertheless, the fact that similar drill hole densities of 1 borehole every 175-250 meters allow for minimizing the variation between the interpreted and the original section for the three

different case studies tends to overcome this limitation. This suggests that for this particular drill hole density, the spacing between boreholes is narrow enough to intercept most significant changes in the geotechnical domains boundaries. This explains the significantly lower variation between the interpreted and the original sections for drill hole densities of 1 borehole every 175-250 meters and higher drilling densities.

It is recognised that the interpretation of the geological sections is subjective as it depends on the experience of the interpreter. Consequently, such interpretation may vary from one person to another. For the analyses, the influence of having different interpreters for the geological sections was not investigated. The interpretation by only one mining engineer constitute a limitation of the proposed guidelines. Nevertheless, the sections in this review were revised by the authors and by an independent geologist and it is believed that a similar trend would be observed with another interpreter. Irrespective of the approach used to delineate the contacts between the different domains, there is need to validate that the defined contacts are in agreement with the geological settings and the formation environment for the deposit under considerations. Furthermore, the quality of the interpreted contacts is defined by the quantity of data used (i.e. the number of domains interceptions obtained from the boreholes). Regardless of the method used (i.e. a simple interpretation from a geologist or numerical methods), the drilling density will significantly influence the resulting geological model.

Another limitation of this investigation is the simulation of vertical boreholes. Effectively, the interpretation may vary with inclined boreholes and even with boreholes with different inclination. However, no significant effect was noted with the section analysed with inclined boreholes at Mine C. It is recognised that the use of vertical boreholes may be inadequate to identify sub-vertical structural features such as dykes, folds, faults, etc. An element of judgement is required to use oriented boreholes for the specific cases where such structures are expected. Those features can be anticipated from other sources of information collected prior to the geotechnical drilling campaign (e.g. geological settings, regional mapping, outcrop mapping, etc.).

It is recognised that the 2D interpretation of only one section per mine site do not account for the variation of the geological contacts in 3D. For this research, the 2D section is considered to be the first input to the 3D model and similar drill hole density are expected for other 2D sections on the same site. With the increasing popularity of implicit 3D modelling, the effect of comparing 3D volumes instead of 2D sections could be investigated, but this was outside the scope of this paper. Regardless of the analysis method used to establish the geological contacts (i.e.

3D volumes interpreted from 2D sections or implicit 3D modelling), the quality of the geological model will depend on the number of sampling boreholes used to determine the rock types and establish the geological model. The objective of this paper is to suggest practical preliminary guidelines to evaluate the number of boreholes required while planning a drilling campaign at early stages of a mining project. The use of complex statistical approaches may be of greater values at later stages when more data are available to validate the selected drilling density.

It was observed that the number of geotechnical domains identified at the same site influences the results. The method of analysis is based on the percentages of variation of the interpreted section from the original model. If few geotechnical domains are identified (e.g. Mine B), the percentage of variation is likely to be less because the domains cover a greater area and the probability to intersect the domain with a smaller drill hole density is higher than for a domain with a small area. This explains why the percentage of variation is more significant at Mine C, for which a higher number of geotechnical domains with a smaller area are identified. The complexity level should also account for the continuity of the domains. If some domains are represented by lenses (e.g. ore deposit at Mine C), a high complexity level should be assigned even if the geological and structural complexity levels are considered low.

In addition, the interpretation of the country rock geological sections do not account for the information already available from the resource and reserves estimation. The drill hole density to define the geological model in the vicinity of the ore deposit is likely to be significantly higher than the minimum suggested in the guidelines. The drill hole densities are suggested for the country rock model in which the pit slopes are likely to be located and for which limited information is generally available. Effectively, geotechnical data are usually collected during a more limited drilling campaign subsequent to the original exploration investigations.

It is recognised that the geological model is one component of the geotechnical model. Other components such as the structural model, the rock mass model and the hydrogeological model are also required to establish the geotechnical model (Read and Stacey 2009). A quantity of data required to establish the other components of the geotechnical model is collected from sampling geotechnical boreholes (e.g. rock core samples to conduct laboratory testing, structural data from oriented boreholes or televiwers, water levels from piezometers, etc.). The drilling density required to collect these data with a sufficient level of confidence could be different than the drilling density presented in Table 5. The integration of the different components of the geotechnical model within the same drilling campaign was not investigated in this paper. The drilling density suggested in Table 5 should be adjusted to

optimize the data collection campaign to account for all geotechnical data required for the purpose of the work to be performed.

Finally, these are preliminary guidelines based on three case studies of quality field data. Extending this analysis to other sites with different geological and structural settings may eventually contribute to improving the guidelines. However, the guidelines provide a quantified indication of the potentially required drill hole density based on case studies. This constitutes a major contribution because such quantification was not previously available to the mining industry. The practical implications of the developed guidelines to the mining industry or for any other design that requires a geological model are discussed in Section 7.

7. Practical implications

7.1. Constructing a new geological model

For a new project, for which a geological model is required as part of the geotechnical model, it is assumed that the complexity level of the geotechnical domains can be obtained from information collected from the previous geological drilling campaign(s) conducted for the resources and reserves estimation. Given that geological boreholes are generally located in the vicinity of the ore deposit, additional information is often required for the slope design in the areas where the pit slopes will be located. The proposed guidelines (Table 5) can be consulted to select a minimum drill hole density, based on the complexity level of the geotechnical domains and on the maximum acceptable variation of the interpreted geological model from the real rock mass. If the geotechnical domains cannot be previously identified, the drilling campaign could start assuming a low complexity level for the geotechnical domains, but sufficient funds should be allocated in order to increase drill hole density if higher complexity domains are encountered.

7.2. Updating a geological model

In cases that there is an existing database for the identification of the geotechnical domains, the proposed guidelines (Table 5) can be consulted to evaluate if the drill hole density used for core logging and geological modelling is acceptable. This implies that it is in the range suggested in the guidelines for the assigned complexity level and the maximum acceptable percentage of variation from the real rock mass. If the previously selected drill hole density is considered too low and significant variations between the geological model and the site conditions are observed,

further drilling should be considered in order to validate the geological model and to modify the slope design if deemed necessary. The proposed guidelines can be useful in the planning of subsequent drilling campaigns required for expansion purposes of an open pit.

8. Conclusions

This paper presented a quantified assessment of drilling additional boreholes on the quality of a geological model. Boreholes were simulated in three case studies geological models to quantify the variation of the interpreted section from the original section for different drill hole densities. The results for the three case studies showed a similar trend, i.e. the variation between the interpreted section and the original section is less significant for a drill hole density of 1 borehole every 175-250 meters. However, it was recommended that the drill hole density should vary according to the geotechnical domain complexity, i.e. more boreholes should be drilled for higher complexity domains. To account for the geotechnical domain complexity (low, medium, high), a classification system was developed to assign complexity levels to the geotechnical domains. Empirical guidelines for the minimum number of boreholes to define the geological model per domain complexity and for a maximum variation from the real rock mass were developed.

The proposed guidelines are preliminary and based on three case studies. The interpretation of the geological sections does not account for the information already available from the resource and reserves estimation. The drill hole density to define the geological model in the vicinity of the ore deposit is likely to be significantly higher than the minimum suggested in the guidelines. The proposed drill hole densities are applicable for country rock models in which the pit slopes are likely to be located and for which limited information is generally available. The guidelines provide a quantifiable indication of the potential drill hole density required to minimize the variation of the interpreted geological model from the real rock mass. This constitute a major contribution because such quantification was not previously available to the mining industry. Drilling a minimum number of boreholes for a maximum variation of the interpreted model vs. the real rock mass can give more flexibility to the designer depending on the level of information required for the purposes of the work to be performed. The suggested guidelines can be used in a variety of projects in rock mechanics and engineering geology.

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References

- Braun, D. 1991. Ore interpretation and its relationship to dilution. 93rd Annual General Meeting. Canadian Institute of Mining and Metallurgy, Vancouver.
- Canadian Institute of Mining (CIM). 2003. Estimation of mineral resources and mineral reserves, best practice guidelines [online]. Canadian Institute of Mining Council: 53p. Available from <http://web.cim.org/UserFiles/File/Estimation-Mineral-Resources-Mineral-Reserves-11-23-2003.pdf> [cited 25 August 2017].
- Dassault Systemes. 2015. GEMS Version 6.7.2. Collaborative Geology and Mine Planning solution [online]. Available from <http://www.geovia.com/products/GEMS>, Toronto, Ontario, Canada [cited 10 November 2017].
- Fillion, M.-H., and Hadjigeorgiou, J. 2017. Quantifying the Impact of Additional Laboratory Tests on the Quality of a Geomechanical Model. *Rock Mechanics and Rock Engineering*, **50**: pp. 1097-1121.
- Hadjigeorgiou, J. 2012. Where do the data come from? *In* Proceedings of the Sixth International Seminar on Deep and High Stress Mining, Perth, Australia, 28-30 March 2012. Australian Centre for Geomechanics, *Edited by* Y. Potvin, Nedlands, W.A., pp. 259-278.
- Haile, A. 2004. A Reporting Framework for Geotechnical Classification of Geotechnical Classification of Mining Projects. *Australasian Institute of Mining and Metallurgy Bulletin*: pp. 30-37.
- Higgins, M. W. 1971. Cataclastic rocks: United States Geological Survey Professional Paper 687: 97p.
- International Society for Rock Mechanics (ISRM), 1975. Recommendations on site investigation techniques. ISRM Commission Report, July 1975: 64 p.
- JORC. 2012. Australian Joint Ore Reserves Committee. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves [online]. The Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists, and Minerals Council of Australia. Available from http://www.jorc.org/docs/JORC_code_2012.pdf [cited 25 August 2017].

- Read, J. 2009. Data Uncertainty. *In* Guidelines for Open Pit Slope Design. *Edited by* J. Read and P. Stacey. CSIRO Publishing, Collingwood. pp. 213-220. ISBN: 9780415874410.
- Read, J., and Stacey, P. 2009. Guidelines for Open Pit Slope Design. *Edited by* J. Read and P. Stacey. CSIRO Publishing, Collingwood. 496 p. ISBN: 9780415874410.
- Scoble, M.J., and Moss, A. 1994. Dilution in underground bulk mining: implications for production management. Geological Society, London, Special publications, **79**: pp. 95-108, doi:10.1144/GSL.SP.1994.079.01.10.
- Steffen, O.K.H. 1997. Planning of open pit mines on a risk basis. The Journal of the South African Institute of Mining and Metallurgy, **97** (2): pp. 47-56.
- Steffen, O.K.H. 2014. Risk Management in Geotechnical Engineering and Open Pit Mine Planning. *In* Proceedings of the 1st International Conference on Applied Empirical Design Methods in Mining, Lima, Peru, 9-11 June 2014. Sociedad Peruana de Geoingenieria, Lima, Peru, 16 p.
- Terbrugge, P.J., Contreras, L.-F., and Steffen, O.K.H. 2009. Value and Risk in Slope Design. *In* Proceedings of the Slope Stability Conference, Santiago, Chile, 9-11 November 2009. Faculty of Engineering of Universidad de los Andes, Santiago, Chile and CSIRO Exploration & Mining, Brisbane, Australia, 7 p.

Figure Captions

Figure 1. Interpreted geological section according to 100 foot, 50 foot and 25 foot information interpretation (Braun 1991).

Figure 2. Cross section through Mine A country rock model (Modified from I. J. Basson and D. Tennant, personal communication, July 2012).

Figure 3. Mine B Country rock model (Modified from I. J. Basson, personal communication, January 2012).

Figure 4. Plan view and cross section of the country rock model at Mine C (Modified from D. Tennant and I. J. Basson, personal communication, November 2013).

Figure 5. Methodology for calculating the variation of the interpreted section from the original section for a given drill hole density (example for Mine A).

Figure 6. Example of the interpretation of three different 2D sections at Mine A.

Figure 7. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine A.

Figure 8. Example of the interpretation of three different 2D sections at Mine B.

Figure 9. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine B.

Figure 10. Example of the interpretation with vertical holes for two different 2D sections at Mine C, Sector 1.

Figure 11. Example of the interpretation with inclined holes for two different 2D sections at Mine C, Sector 2.

Figure 12. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 1.

Figure 13. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 2 (vertical boreholes).

Figure 14. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 2 (inclined boreholes).

Figure 15. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 3.

Figure 16. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains with (a) low complexity (b) medium complexity and (c) high complexity.

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Table 1. Sections analysed and simulated drill hole densities for the three mine case studies.

Case study	Mine A	Mine B	Mine C		
Section	W – E	W – E	E – W Sector 1	E – W Sector 2	E – W Sector 3
	Vertical boreholes	Vertical boreholes	Vertical boreholes	Vertical and Inclined boreholes	Vertical boreholes
Drill hole densities (i.e. spacing between boreholes) (x) = number of boreholes on the 2D section	550m (2)	890m (3)	900m (3)	900m (3)	900m (3)
	480m (3)	650m (4)	800m (4)	800m (4)	800m (4)
	390m (4)	550m (5)	700m (5)	700m (5)	700m (5)
	350m (5)	450m (6)	600m (6)	600m (6)	600m (6)
	280m (6)	390m (7)	500m (7)	500m (7)	500m (7)
	230m (7)	350m (8)	450m (8)	450m (8)	450m (8)
	215m (8)	280m (9)	400m (9)	400m (9)	400m (9)
	185m (9)	230m (11)	350m (10)	350m (10)	350m (10)
	175m (10)	215m (13)	300m (11)	300m (11)	300m (11)
	155m (11)	185m (15)	250m (12)	250m (12)	250m (12)
	140m (12)	175m (16)	200m (15)	200m (14)	200m (13)
	125m (13)	155m (18)	150m (19)	150m (20)	150m (18)
		140m (20)			
		125m (22)			

Table 2. Minimum drill hole density (i.e. spacing between boreholes) for each mine site that results in a less than 10% variation of the interpreted section from the original model for most geotechnical domains.

Case study	Mine A	Mine B	Mine C			
Section	W - E	W – E	E – W Sector 1	E – W Sector 2		E – W Sector 3
				Vertical	Inclined	
Spacing between boreholes resulting in <10% variation for most domains	175m	230m	200m	200m	150m	150m

Table 3. Classification system for defining the complexity level (low, medium, high) of the geotechnical domain.

Low complexity	Medium complexity	High complexity
1 rock type	2-3 rock types	Multiple rock types
Homogeneous rock mass	Different competencies	Tectonically affected areas
Granitic and plutonic rocks	Faults but no crustal plate movement	Shear zones
Coal	Sedimentary rocks:	Intense deformation
Kimberlites	Shales + Mudstones	Folding
Iron Manganese Deposits	Limestone	Metamorphic rocks:
	Conglomerate	Schists
	Gritstone	Metapelite
	Sandstone	Phyllite
	Breccia	Argillite
	Chert	Paragneiss
	Metamorphic rocks:	Quartzite with mica inclusions
	Gneiss	Highly weathered sedimentary rocks (rippable)
	Marble	
	Metacarbonate	
	Quartzite	
	Intrusions:	
	Dykes and sills	
	Diabase	
	Vein Quartz	

Table 4. Suggested levels of geotechnical effort and targeted levels of data confidence in the geological model by project stage for an open pit mine project (modified from Read and Stacey 2009).

Project level status	Project stage				
	Conceptual	Pre-feasibility	Feasibility	Design and construction	Operations
Geotechnical level status	Level 1	Level 2	Level 3	Level 4	Level 5
Geological model	Regional literature; advanced exploration mapping and core logging; database established; initial country rock model	Mine scale outcrop mapping and core logging; enhancement of geological database; initial 3D geological model	Infill drilling and mapping; further refinement of geological database and 3D model	Targeted drilling and mapping; refinement of geological database and 3D model	Ongoing pit mapping and drilling; further refinement of geological database and 3D model
Target levels of data confidence	> 50%	50 – 70 %	65 – 85 %	80 – 90%	> 90%

Table 5. Suggested drill hole density for geotechnical boreholes per domain complexity based on the maximum variation from the real model.

Project stage	Variation from real model (%)	Drill hole density per domain complexity Spacing between boreholes (1 hole every ‘X’ meters)		
		LOW	MEDIUM	HIGH
Conceptual	< 50%	900 m	350 m	250 m
Pre-Feasibility	30 – 50 %	900 m	250-350 m	175-250 m
Feasibility	15 – 35%	350-900 m	150-250 m	150-175 m
Design & Construction	10 – 20 %	300-600 m	150-175 m	< 150 m
Operations	< 10%	< 300 m	<150 m	< 125 m

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Figure 1. Interpreted geological section according to 100 foot, 50 foot and 25 foot information interpretation (Modified from Braun, 1991).

136x212mm (300 x 300 DPI)

Figure 2. Cross section through Mine A country rock model (Modified from I. J. Basson and D. Tennant 2012, unpublished report).

239x195mm (96 x 96 DPI)

134x120mm (300 x 300 DPI)

Figure 4. Plan view and cross section of the country rock model at Mine C (Modified from D. Tennant and I. J. Basson 2013, unpublished report).

269x201mm (300 x 300 DPI)

163x190mm (220 x 220 DPI)

Figure 6. Example of the interpretation of three different 2D sections at Mine A.

165x83mm (220 x 220 DPI)

Figure 7. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine A.

180x51mm (300 x 300 DPI)

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Figure 8. Example of the interpretation of three different 2D sections at Mine B.
165x67mm (220 x 220 DPI)

Draft

Figure 9. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine B.

180x48mm (300 x 300 DPI)

Draft

Figure 10. Example of the interpretation with vertical holes for two different 2D sections at Mine C, Sector 1.

165x108mm (220 x 220 DPI)

Figure 11. Example of the interpretation with inclined holes for two different 2D sections at Mine C, Sector 2.

165x107mm (220 x 220 DPI)

Figure 12. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 1.

180x46mm (300 x 300 DPI)

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Figure 13. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 2 (vertical boreholes).

180x43mm (300 x 300 DPI)

Draft

Figure 14. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains at Mine C, Sector 2 (inclined boreholes).

180x54mm (300 x 300 DPI)

180x46mm (300 x 300 DPI)

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Figure 16. Percentage of variation of the interpreted section from the original model for different drill hole densities for the geotechnical domains with (a) low complexity (b) medium complexity and (c) high complexity.

180x178mm (300 x 300 DPI)