Engineering Geology 203 (2016) 140–150

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Developing 3-D mine-scale geomechanical models in complex geological environments, as applied to the Kiirunavaara Mine

J. Vatcher [a,*], S.D. McKinnon [b], J. Sjöberg [c]

[a] Division of Mining and Geotechnical Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
[b] The Robert M. Buchan Department of Mining, Goodwin Hall, 25 Union St. Queen's University, Kingston, Ontario, K7L 3N6, Canada
[c] Itasca Consultants AB, Aurorum 2, SE-977 75 Luleå, Sweden

A R T I C L E I N F O

Article history:
Received 10 May 2015
Received in revised form 7 July 2015
Accepted 16 July 2015
Available online 23 July 2015

Keywords:
Geomechanical model
Geostatistics
Structural domaining
Rock mass characterisation
Alteration
Rock mass behaviour

A B S T R A C T

An understanding of the relationship between the geological environment and rock mass behaviour induced by mining activities can lead to hazard reduction through knowledge-based design. However, characterisation of complex and heterogeneous rock masses that typify mining environments is difficult. A methodology to characterise these types of rock masses, based largely on classical statistics, geostatistics and an extension of previous quantitative structural domaining work, is presented and applied to the Kiirunavaara Mine, Sweden. In addition to a new perspective on intact rock strengths of geological units at the mine, a correlation was found between modelled volumes of clay, modelled RQD, newly identified structural domains and falls of ground. These relationships enabled development of a conceptual model of the role of geology in rock mass behaviour at the mine. The results demonstrate that the proposed methodology can be useful in characterisation of complex rock masses.

1. Introduction

Mining induced rock mass behaviour is a result of the interaction between the mining and geological environments. An understanding of the role of 3-D geomechanical characteristics in rock mass behaviour can lead to significant opportunities for risk-mitigating engineering design. Typically, geomechanical models of mining environments are developed by using classification methods such as Geological Strength Index (GSI) or Rock Mass Rating (RMR). These methods were originally developed and calibrated for civil engineering excavations, such as tunnels, and are well suited to homogeneously jointed rock masses. Alone, however, they are unsuited to heterogeneous rock masses in which the strength and stiffness is affected by characteristics in addition to discontinuities, which typify the geological environment of many mines. Adaptations of GSI for heterogeneous rock masses have been developed (Hoek and Karzulovic, 2001; Marinos and Hoek, 2001); however, they are still mostly based upon planes of weakness, and as identified by Mandrone (2006), are less applicable when weakness exists in other forms, such as alteration. Over the life of a mine, geomechanically relevant data is often collected for different purposes, and there can be difficulty synthesizing these multiple sources of data into a coherent geomechanical model. Also, data availability and coverage issues specific to mining caused by economical and physical constraints (such as shotcreting limiting available mapping faces) often compound the difficulties associated with this process.

This paper proposes a methodology to create a 3-D mine-scale geomechanical model for complex and heterogeneous rock masses using readily available data from mines, such as geologically logged core, Rock Quality Designation (RQD) and mapped discontinuities. Luossavaara-Kiirunavaara Aktiebolag's (LKAB) Kiirunavaara Mine, in northern Sweden, is used to illustrate the techniques. This geomechanical model created for the mine is then compared to fall of ground information, with the intention of developing a conceptual model of causes of rock mass behaviour and identifying indicators of problem areas. In 2008, the Kiirunavaara Mine became seismically active (refer to Dahnér et al. (2012) for a detailed description). Several studies were undertaken by LKAB to understand the underlying causes and nature of the behaviour (Sjöberg et al., 2011, 2012; Vatcher et al., 2014). Recent underground mapping, core logging and laboratory testing campaigns done in support of these projects have revealed that the rock mass is heterogeneous, with variable characteristics across both the 5 km length and > 1000 m depth of the orebody. An additional potential complication for geomechanical characterisation of the rock mass is that there are volumes of clay alteration, which are often meters to tens of meters in their longest dimension.

Previous studies at the Kiirunavaara Mine have been limited in scope with respect to development of a geomechanical model. The majority of these studies were limited in breadth of analysis, often focusing on portions of the available data at the time of each study (Henry and

* Corresponding author.
E-mail addresses: Jessica.Vatcher@LTU.se (J. Vatcher), Steve.McKinnon@queensu.ca (S.D. McKinnon), Jonny@Itasca.se (J. Sjöberg).

http://dx.doi.org/10.1016/j.enggeo.2015.07.020

Marcotte, 2001; Lindgren, 2013; Mattsson et al., 2010; Rådberg et al., 1989). Much additional data collection and analysis has been done since these studies with the intention of increasing the geomechanical understanding of the rock mass, providing a good opportunity to enhance knowledge.

The data analysis techniques presented to create large-scale 3-D geomechanical models were intentionally selected for their compatibility with characteristics of the geology and typical limitations associated with data from mining environments, such as sparse coverage and few samples. The methodology utilises standard statistical tests, geostatistics, and an extension of previously published techniques related to quantifiable identification of structural domains.

2. Kiirunavaara Mine

The Kiirunavaara Mine is a large sublevel caving mine that produces approximately 28 million tonnes per annum of iron ore. With the deepest production levels currently at approximately 800 m below surface (Level 1051 m), the rock mass is seismically active and rockburst prone. The newest main haulage level is Level 1365 m (see Fig. 1), and sublevels currently have a 28.5 m separation. Mine coordinates are approximately aligned with the cardinal directions, and the Y coordinates (positive axis aligned with south), which crosscut the orebody, are used to divide the orebody into blocks for production and ore handling (see the numbered ore pass groups along the orebody in Fig. 1).

The magnetite orebody extends approximately 5 km along strike, which is nearly north–south, with a varying width from meters to over 150 m and a dip of 50-70° towards the east (positive X-axis in mine coordinates). For a detailed description of the geology, refer to Geijer (1910). The most specific geological classifications at the mine are done during core logging, whereas underground geological mapping uses more generic geological classifications. The mine distinguishes ore rock types based on their grade and contaminant concentration. Footwall rock types are divided into three major classifications; granite, skarn or trachyte-trachyandesite (referred to as syenite porphyries at the mine). The trachyte-trachyandesite is further divided into 5 subgroups based on their mineralogy, texture and/or alteration, referred to as Sp1 through Sp5. Porphyry dykes are also common in the footwall region. Hangingwall material, mainly rhyodacite (referred to as quartz-bearing porphyries at the mine), is similarly divided into 5 subcategories (Qp1 through Qp5) based on their mineralogy, texture and/or alteration. Underground geological mapping identifies the ore units based on grade and contamination (the same units as mapped during core logging), however footwall and hangingwall materials are mapped in less detail underground than they are during core logging. Fewer hangingwall data are available by either mapping or core logging due to underground access and ore-targeted drilling.

Some of the rock mass at the Kiirunavaara Mine has undergone significant alteration. This alteration is in the form of both replacement of minerals by clay as well as leaching, leaving the rock porous (Berglund and Andersson, 2013). The clay-altered lens-shaped volumes are visible underground and in core from diamond drilling (as clay and possibly as core losses), and their extent ranges from centimeters to tens of meters throughout the mine.

3. Data and methodology

The selection of data was based on potential importance to geomechanical characterisation, availability, and reliability. Data analyzed in the development of the geomechanical model of the mine was selected because of their possible relations to intact rock strength, zones of strength and stiffness contrasts, rock mass quality and structural domains. The forms of these data sources available at the Kiirunavaara Mine are described below. Some of this data is routinely collected at the mine, and some was collected during specifically targeted campaigns in support of this and other projects at the mine.

- The diamond drill core database consists of approximately 590 000 m of mostly 28 mm diameter core, from approximately 3000 boreholes (LKAB, 2014a). The extent of the data is shown by Volume A in Fig. 2. With few exceptions, all drilling is from underground, with fans of four holes on average at 50 m spacing along strike targeting orebody definition. The majority of drilling is done from the footwall due to access restrictions. On surface, geologists log these drill holes, identifying geological units, core losses and zones of poor material (such as clay), and RQD.
- A total of 56 unconfined compressive strength (UCS) tests were completed on 11 of the rock units, which are sourced from previous testing done by LKAB employees (such as Andersson and Israelsson,

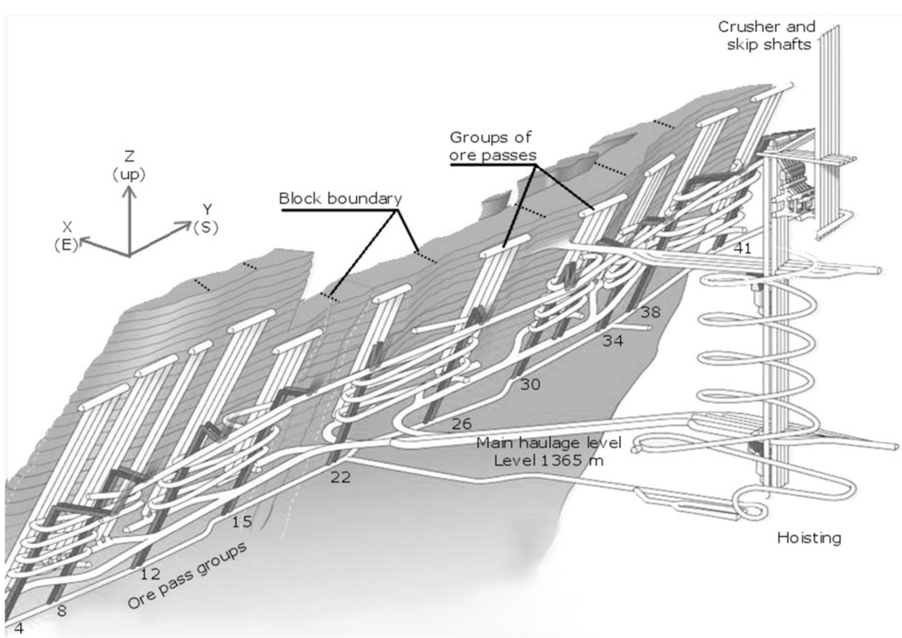

Fig. 1. Sketch of the orebody and mine layout. Production blocks and associated ore pass groups are numbered based on their Y coordinate (numbered at the draw points in this image). Modified image from LKAB.