PERGAMON

International Journal of Rock Mechanics & Mining Sciences 39 (2002) 243–255

International Journal of
Rock Mechanics
and Mining Sciences

www.elsevier.com/locate/ijrmms

Application of two-level factorial design to sensitivity analysis of keyblock statistics from fracture geometry

P. Starzec[a,*], J. Andersson[b]

[a] Swedish Geotechnical Institute, Chalmers Vasa, Hugo Grauers gata 5B, SE-412 96 Gothenburg, Sweden
[b] JA Streamflow, Stockholm, Sweden

Accepted 5 March 2002

Abstract

A stochastically modeled fracture network offers potential for more realistic assessment of stability status in underground excavations than predictions based entirely on deterministic features. The reliability of probabilistic models, however, depends strongly on an accurate estimation of the model's variables, i.e., the fracture network properties from the field and laboratory observations.

In this study, predictions of keyblocks by implementing stochastically generated fractures in the Central Storage Facility for Spent Nuclear Fuel (CLAB 2 Centralt Lager Använt Bränsle) located in southeast Sweden are presented. The fracture network model is built by using fracture mapping in the floor of the facility and incorporates fracture size, shape, orientations, termination mode, spatial arrangement and fracture mechanical properties. The predicted volume of individual keyblocks is best-fitted with the Pareto probability distribution function. Subsequently, a statistical two-level factorial analysis is performed to examine the impact of both single fracture properties and their interactions on the predictions made. In the factorial experiments, the block predictions are made for eight different fracture models where three factors: fracture radii, orientation and termination are each assigned two levels intentionally departing from the best estimates found for the CLAB 2 site. This allows us to express the experiment results as the degree to which each of the eight computed block statistics deviated from the most likely prediction. It is found that fracture orientation is the only statistically significant factor influencing the keyblock statistics while the input from other variables/fracture properties and their interactions is less significant.

The results of our study yield a prospective approach for improving the effectiveness of the stochastic model variable estimation and for more optimal field mapping strategies.

1. Introduction

The volume, shape and amount of unstable rock blocks formed by intersections between joints/fractures and contours of underground chambers/tunnels depend on both the dimensions and the geometry of the excavation itself as well as on the geometry and other properties of fractures/joints intersecting the excavation.

The commonly applied Block Theory of Goodman and Shi [1] focuses on the potentially largest keyblocks and orientations of major joint systems in relation to the orientation of the underground object. Several authors [2–5] attempted to employ a probabilistic approach for keyblock predictions based on the stochastic representation of fracture geometries and their locations. Many other researchers addressed the predictions of unstable rock blocks both for underground facilities and for rock slopes, and the numbers of the numerical codes for keyblock predictions and rock support design have been developed; SATIRN [6], UNWEDGE [7,8], DRKBA [9], MSB [10], KBTUNNEL [11], to mention only a few. These codes are all based on similar principles but differ in terms of the type of input data, model assumptions and potential outcome from the simulation analysis. Other well-known codes/methodologies offer less potential for modeling more complex fracture networks but on the other hand permit the examination of interactions between block triggering, displacement, deformation and stress field in relation to the time factor: for example, 3DEC [12] and DDA [13].

*Corresponding author.
E-mail address: peter.starzec@swedgeo.se (P. Starzec).

1365-1609/02/$ - see front matter
PII: S1365-1609(02)00026-6

One important aspect of keyblock analysis refers to the estimation process of fracture geometries and mechanical properties based on field and/or laboratory measurements. Depending on the type of estimated fracture variable/property, its uncertainty will have a different impact on the final block predictions. Further, in some circumstances the interactions between several variables may influence the predictions to a higher degree than the individual variables do. Knowing which fracture properties significantly affect the amount of unstable blocks, their size or total removable volume along an underground chamber and which properties are of less importance could result in the optimization of field sampling strategy and of more cost-effective tunnel support design. The majority of these kinds of studies have been focused on how predicted block statistics depends on varying one property at the time e.g., by varying fracture size, fracture intensity or tunnel dimensions [14–16].

Therefore, a deeper analysis of the possible interactions among properties of the fracture network and their quantitative bearing on block predictions could help us make more reliable geological risk estimates. This paper presents: (i) probabilistic three-dimensional keyblock predictions based on two-dimensional fracture mapping from the floor of the CLAB 2 underground chamber hosted in crystalline rock unit, southeast Sweden, and (ii) sensitivity analysis of keyblock predictions to fracture size, orientations and terminations based on statistical two-level factorial design.

2. Stochastic model of fracture network at the CLAB 2 site

2.1. Fracture mapping data at the CLAB 2 site

The probabilistic keyblock predictions imply that simulation of potentially unstable rock blocks relies on a stochastic fracture field generated from observed/measured fracture properties. In the current work, the FracMan fracture generator was applied [17] allowing us to represent such properties as fracture orientations, size, shape, termination mode, intensity and spatial arrangement with the best-fit continuous statistical distributions or mathematical/statistical processes estimated from measured quantities at the site.

The process of model generation should be preceded by studies on structural/geological homogeneity of the site to determine whether or not fracture properties are spatially independent. Relying on results from such study, the modeled rock portion is represented either by stationary models where fracture properties exhibit the same statistical moments within the entire volume or by nonstationary or multidomain models, i.e., an assembly of more than one stationary model where each model represents a different tectonic/structural or lithological unit. Although there are no strict procedures designed entirely for homogeneity studies on fracture geometries, a good start is to apply non-parametric equivalents to classical p- and F-statistics [18] for testing mean and variance of a variable in question within different sample populations (different lateral and/or vertical locations at the site) and gradually switch to more advanced statistical procedures. Kulatilake et al. [19] make inferences about the statistical homogeneity of jointed rock mass by studying the spatial variation of box fractal dimension for trace lengths. Dershowitz and Ushida [20], give an overview of several methods for spatial analysis of fracture field data including trend analysis.

In a previous study [21], the geological/structural homogeneity at the CLAB site was investigated by using non-parametric Kolmogorov–Smirnov, Mann–Whitney and Kruskal–Wallis tests on fracture intensity obtained from a number of boreholes. Also, the moving average for fracture intensity vs. depth was calculated to account for possible trends in vertical direction. However, the results did not show any clear signs of anisotropic or inhomogeneous fracturing pattern and a one-domain, stationary stochastic model was adopted for the site.

The excavated CLAB 2 chamber is intended to serve as an interim storage facility for spent nuclear fuel. It is located about 25 m underground and is 115 m in length, 21 m in width and 27 m in height. Fig. 1 shows fractures and weakness zones mapped on the floor of the cavern divided in the figure into two sections 57.5 m long each (Fig. 1a depicts the northern half of the floor and Fig. 1b the southern half). While in the previous work on keyblock predictions for the site the veins and the large-aperture fractures were selected for fracture network generation [21], in this study the access to the mapped fracture trace data made it possible to apply a more geomechanically reliable criterion for the selection of the proper type of discontinuities for setting up a stochastic fracture model. According to geological expertise at the site [22], the open fractures and the fractures filled with chlorite were the most significant for keyblock prediction due to their low shear strength compared to tight fractures or to those filled with quartz. For the purpose of stochastic fracture network modeling, we selected 411 fractures as a representative hard data-input for variable estimation. The shortest trace length selected was 1.1 m long and the longest trace was 25 m long, but longer traces were also expected since a certain number of the mapped traces were censored by the floor's boundaries.

The approach adopted in the FracMan code is that the observed statistics for fracture geometric properties obtained from 1D and/or 2D fracture mapping are approximated with theoretical probability density functions and, consequently, each generated fracture in the