International Journal of Mining Science and Technology 26 (2016) 461–470

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

Science of empirical design in mining ground control

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ARTICLE INFO

Article history:
Received 25 July 2015
Received in revised form 30 October 2015
Accepted 10 January 2016
Available online 19 March 2016

Keywords:
Design
Pillar
Stope
Empirical
Statistics
Modeling

ABSTRACT

Many problems in rock engineering are limited by our imperfect knowledge of the material properties and failure mechanics of rock masses. Mining problems are somewhat unique, however, in that plenty of real world experience is generally available and can be turned into valuable experimental data. Every pillar that is developed, or stope that is mined, represents a full-scale test of a rock mechanics design. By harvesting these data, and then using the appropriate statistical techniques to interpret them, mining engineers have developed powerful design techniques that are widely used around the world. Successful empirical methods are readily accepted because they are simple, transparent, practical, and firmly tethered to reality. The author has been intimately associated with empirical design for his entire career, but his previous publications have described the application of individual techniques to specific problems. The focus of this paper is the process used to develop a successful empirical method. A six-stage process is described: identification of the problem, and of the end users of the final product; development of a conceptual rock mechanics model, and identification of the key parameters in that model; identification of measures for each of the key parameters, and the development of new measures (such as rating scales) where necessary; data sources and data collection; statistical analysis; and packaging of the final product. Each of these stages has its own potential rewards and pitfalls, which will be illustrated by incidents from the author's own experience. The ultimate goal of this paper is to provide a new and deeper appreciation for empirical techniques, as well as some guidelines and opportunities for future developers.

1. Introduction

Design is the central engineering activity. It is a process which combines knowledge and judgement to obtain a desired outcome. Models are a crucial element in the design process, even though all models are limited in their ability to represent real systems.

In their seminal 1988 paper, Starfield and Cundall introduced a classification of modeling problems (Fig. 1) [1]. The *X*-axis measures the level of understanding of the fundamental mechanics of the problem to be solved. The *Y*-axis refers to the quality and/or quantity of the available data, including material properties, boundary conditions, and past experience. In many branches of mechanics, most problems fall into region III, where there is both good understanding and reliable data. This is the region where numerical models can be built, validated, and used with conviction.

Starfield and Cundall argued that problems in rock mechanics usually fall into the data-limited categories II or IV. The "triangle diagram" shown in Fig. 2, helps explain why. It indicates that the three "end-members" of rock mass behavior are: (1) massive, strong rock that behaves elastically and is subject to brittle failure; (2) blocky rock, where deformation and failure occurs exclusively along well defined joint systems; and (3) soil-like rock, which is subject to shear failure through the rock mass.

Most real rock masses fall somewhere in the middle of this triangle plot. This is why it has proved so difficult to build and use numerical models. It is not enough that the model itself incorporates the many different failure modes, but it must have quality input properties and boundary conditions (in situ stresses) to match. Starfield and Cundall concluded that a more experimental use of models was appropriate for geomechanics.

In the field of mining ground control, however, many problems actually fall into Starfield and Cundall's region I. Our understanding of the complex mechanical behavior and properties of rock masses may be limited, but the potential for data collection is huge. Hundreds of stopes and panels are mined each year, and each one is a full-scale test of a mine design. As Jack Parker noted in 1974, "scattered around the world are millions and millions of pillars-the real thing-under all imaginable conditions; and

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http://dx.doi.org/10.1016/j.ijmst.2016.02.015
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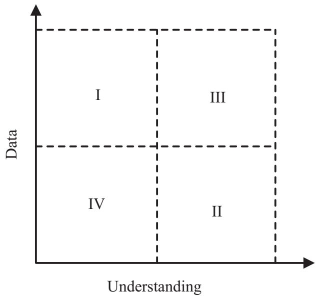

Fig. 1. Classification of modeling problems [1].

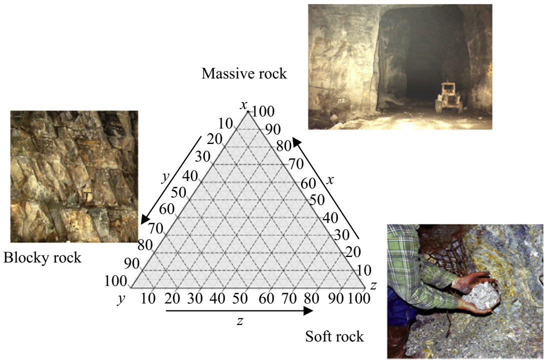

Fig. 2. Triangle plot showing the three end members of rock mass behavior.

tabulating their dimensions, the approximate loads, and whether they are stable or not would provide most useful guidelines for pillar design" [2].

Simply tabulating data does not necessarily lead to useful conclusions, however. Interpreting large data sets with many variables is a science of its own. Fortunately, today's data analysis techniques are far more powerful than those that were available to the mine design pioneers. In the past 30 years, fields like economics, sociology, psychology, anthropology, and epidemiology have all been transformed by quantitative data analysis using statistics. Sophisticated statistical packages enable researchers in those fields and others to efficiently comb large databases for significant relationships between the variables. Even more recently, the business models of some of the most successful corporations in the world are based on "mining" the immense quantities of data available from internet searches, social networking, cell phone usage, and many other sources.

2. History of empirical design

For thousands of years, all mine design was empirical, in the sense of being based on past experience rather than engineering mechanics. However, the first empirical design method that combined case history data with rock mechanics principles appears to have been the one published by Bunting in 1911 [3]. Bunting addressed the issue of pillar sizing for the anthracite coalfields of eastern Pennsylvania. Improper pillar design had caused numerous "squeezes", whose "inherent effects" are "the crushing of the pillars, the caving of the roof, and the heaving of the bottom". After testing hundreds of coal specimens, Bunting concluded that the laboratory strength of anthracite could be represented as:

$$Ss = 12 + 5.2\ (w/h)$$

where Ss is the specimen strength, MPa; w the specimen width; and h the specimen height.

Critically, however, Bunting also had full-scale data in the form of data from actual pillar squeezes. He concluded that the laboratory specimens were approximately 2.5 times stronger than full-size pillars, such that the pillar strength (Sp) was:

$$Sp = 4.8 + 2.1\ (w/h) \tag{1}$$

Fig. 3 shows Bunting's data, and his design curve.

Miklos Salamon was responsible for the next significant advance in the science of empirical design [4]. Following the infamous Coalbrook pillar collapse in which more than 400 South African coal miners died, Salamon was asked to develop guidance to prevent a re-occurrence. First, he collected a case history database of 27 failed and 98 unfailed areas of room and pillar workings. Then he modeled the strength of the pillars using a simple power function, using just the pillar's width and height as input. The model contained three unknown constants, which were estimated using the "maximum likelihood" statistical technique. The resulting "Salamon-Munro formula", or some version of it, has been used in the design of nearly every pillar mined in South Africa since.

Looking back 20 years later, Salamon wrote that empirical methods were a "very powerful, and to an engineer, very satisfying technique to solve strata control problems…the main advantage of this approach is its firm links to actual experience. Thus, if it is judiciously applied, it can hardly result in a totally wrong answer". Salamon did, however, caution that the developer of an empirical method must start with "a reasonably clear understanding of the physical phenomenon in question. This is a feature which distinguishes it from ordinary regression used in statistics" [5].

The next major breakthrough was the development of modern rock mass classification systems in the early 1970s. Today it is hard to imagine the field of rock engineering without the geomechanics rock mass rating (RMR) and rock tunneling quality (Q) systems. Bieniawski stated that rock mass classifications have been successful because they (1) provide a methodology for characterizing rock mass strength using simple measurements, (2) allow geologic information to be converted into quantitative engineering data; (3) enable better communication between geologists and engineers, and (4) make it possible to compare ground control experiences between sites, even when the geologic conditions are very different [6].

The last point is a key reason why rock mass classifications play such an essential role in empirical design. By reducing the overwhelming variety of geologic variables into a single, meaningful, and repeatable parameter, they make it possible to quantify geology and include it in statistical analysis.

The original application of both the Q and RMR systems was to the selection of support for tunnels [7,8]. The Q system in particular was associated with a very large case history database, which

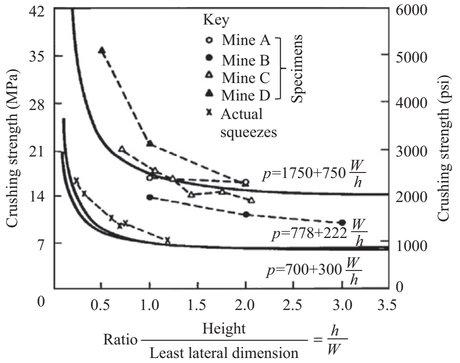

Fig. 3. Empirical formula for the strength of anthracite pillars proposed by Bunting [3].