International Journal of Rock Mechanics & Mining Sciences 46 (2009) 896–904

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Value of information analysis for site investigation programs accounting for variability, uncertainty and scale effects with the Äspö HRL prototype repository as an example

Pär-Erik Back [a,b,c,*], Rolf Christiansson [d]

[a] Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden
[b] Geo Innova AB, Linköping, Sweden
[c] Sweco Environment AB, SE-100 26, Stockholm, Sweden
[d] Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden

ARTICLE INFO

Article history:
Received 8 February 2008
Received in revised form
6 February 2009
Accepted 17 March 2009
Available online 18 April 2009

Keywords:
Value of information
Thermal conductivity
Uncertainty
Decision analysis
Nuclear waste repository

ABSTRACT

An important feature of underground projects is the early site investigations, performed as a means to identify and quantify hazards. A methodology is presented for identifying the most cost-effective investigation program among a set of alternatives. Methodologies are presented for both investigation of thermal conductivity in hard rock and collection of rock mechanic data for stress induced spalling problems. The cost-effectiveness of an investigation program is estimated by means of value of information analysis (VOIA). Each investigation program of thermal conductivity is associated with uncertainty due to natural variability and lack of knowledge. These uncertainties are taken into account in a simulation model with the aim to estimate the distribution of thermal conductivity values at different scales. The output is a set of thermal conductivity values from which a design parameter can be estimated. The simplest measure of the value of a site investigation is the expected reduction of uncertainty of the design parameter.

The methodology is demonstrated with a case study for the prototype nuclear waste repository at Äspö Hard Rock Laboratory, Sweden. A set of four investigation programs for thermal conductivity were evaluated, and the most effective one identified. The application illustrates that an investigation program may supply very different value to a project, depending on how the objective of the investigation is defined. This is demonstrated by using two different objectives and comparing the results. Practical applications of the methodology on both thermal properties and rock mechanics are discussed, with emphasis on site investigations performed by the Swedish Nuclear Fuel and Waste Management (SKB).

1. Introduction

The possibility to influence a project is normally largest in its early phases. An important feature for planned underground projects is the early site investigations, performed as a means to identify and quantify hazards. Early information allows for sufficient time to deal with any identified hazard from a technical or contractual point of view. But the trade-off on when information is sufficient is a decision problem. Each decision is associated with expected costs, as well as potential benefits. More investigations might reduce the predicted project cost, but there are also costs involved in performing the additional investigations. Thus, more information should be collected only if we expect to gain more by obtaining that information than the cost to obtain it. However, at the time of making a decision we may not know how much the additional information will be worth.

The benefit of more investigations depends on how much is already known at the time of decision. The higher the level of knowledge, the less impact the additional information will have on a decision (the principle of diminishing returns). The value of additional information also depends on how effective the investigation is. No investigation of geological conditions is perfect, so there will always be remaining uncertainties, which means that a decision must be made under uncertainty. In particular, if additional investigations of certain properties only slightly decrease the uncertainty, they may not be worthwhile pursuing even if the uncertainty as such is judged to be quite large.

When to end site investigations is a decision problem. The objective of the investigations is not primarily to produce a

* Corresponding author at: Sweco Environment AB, SE-100 26 Stockholm, Sweden. Tel: +46 8 695 66 98.
E-mail address: par-erik.back@sweco.se (P.-E. Back).

1365-1609/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijrmms.2009.03.003

geoscientifically "true" model, but rather to provide a basis for good decisions. Put simply, the site investigations should stop when the expected net gain of further investigations is zero or negative, where gain is related to the expected total cost and benefit, which includes several factors besides the direct monetary outlay. The value of different investigation programs can be estimated by so called value of information analysis (VOIA). In the field of hydrogeology, the term data worth analysis is used for this type of analysis [1]. The basic idea in a VOIA is to estimate the value of additional information by studying how the new information reduces uncertainty, usually in relation to the cost of obtaining the new information. This is performed by analyzing the uncertainty at the present state of knowledge, and comparing it with the reduced uncertainty that is expected when new information becomes available. Thereby, the expected value of an investigation program can be estimated.

The origin of VOIA is decision theory. Some examples of applications in engineering and hydrology date back to the 1970s [2,3]. Several applications in hydrogeology were carried out in the 1990s, introduced by Freeze et al. [4] in a series of papers. Today, VOIA is used, for example, in economics, but there are also examples of VOIA on geo-environmental problems [5–8].

A general discussion of the value of information in SKB's (Swedish Nuclear Fuel and Waste Management) site investigations for a final repository is provided by Andersson et al. [9]. They concluded that the cost and value of information obtained in the site investigation phase, needs to be weighted against the costs and value of obtaining information during later stages. All issues need not be resolved during the site investigation phase; instead, some could be handled in a better way in later phases, e.g. during the construction and detailed investigation phase. More specifically, they recommended to actively soliciting feedback from Safety Assessment and Repository Engineering; keeping track of the uncertainty evaluation of the key aspects of the Site Descriptive Models; developing the Underground Characterization Programme, as this is the next step against which to evaluate whether the surface-based investigations should continue; and occasionally applying formal decision aiding tools as a means to provide further insights into the decision problem, but not as the main mechanism of reaching and motivating decisions.

The purpose of this paper is to address the last recommendation by presenting and applying a methodology for VOIA for investigation programs of thermal properties of rock at potential repository sites for spent nuclear fuel in Sweden. The objective is also to outline a VOIA methodology for investigations regarding rock mechanics, i.e. for the risk for stress induced spalling, where the result depends on two parameters; the uniaxial strength and in situ stress.

An application of the methodology for thermal conductivity is presented for the prototype nuclear waste repository at Äspö Hard Rock Laboratory (HRL), Sweden. Thermal conductivity has a large influence on decisions regarding canister spacing in a final repository. The application demonstrates how the methodology can be applied to a practical problem of identifying cost-effective site investigation programs. As far as known, this paper is the first to apply VOIA for a problem concerning thermal properties of rock.

2. Methodology of value of information analysis

2.1. The objective of investigations

Before VOIA can be performed, it is imperative to explicitly define the objective of the investigation. The objective must be precisely defined, preferably by using a statistical parameter. The advantage of using a statistical parameter is that the uncertainty associated with the parameter can be analyzed in a quantitative VOIA. Less precisely defined objectives makes uncertainty difficult to quantify, resulting in problems of expressing the value of an investigation in quantitative terms.

The choice of statistical parameter is problem specific. In this paper, two objectives for investigation of thermal properties will be used: (1) estimation of the mean thermal conductivity, and (2) estimation of the 2.5-percentile of the thermal conductivity distribution. The objectives of the data collection program for rock mechanics are: (a) estimation of the mean laboratory uniaxial compressive strength, and (b) estimation of the maximum and minimum far-field principal stresses in the plane of analysis.

2.2. The value of information

There are several ways to measure the value of an investigation program. The most appropriate one depends on the problem and the level of ambition in the analysis. It is often desirable to assess the economic value of the investigation. With a risk–cost–benefit approach, both deterministic project costs, investment costs, and investigation costs are considered, as well as probabilistic costs (risks) [1]. This means that both the probability of an undesirable outcome and its consequence are considered. The value of an investigation program can then be expressed as the expected change in total cost of a project as a result of the investigation. Such an approach corresponds to the highest level of ambition and complexity in Fig. 1 (Level 3). This level of ambition can be difficult to apply in very large and complex projects, such as SKB's projects for localizing nuclear waste repositories, where the total project cost depends on a large number of factors and where thermal conductivity and rock mechanics are just two among many. In addition, individuals may conceive some of the costs, especially probabilistic costs (risks), to have very different economic value, adding yet another level of complexity to the analysis.

A less complex and more applicable approach is to include only the investigation costs in the analysis. Thus, the measure of value can be quantified as the quotient of uncertainty reduction and investigation cost, i.e. Level 2 in Fig. 1. Level 2 analyses have been demonstrated in [10] and [7] for contamination problems.

In cases were it is impractical to assess the value in monetary terms, or when investigation costs are not of concern, some surrogate of value is often used [11]. One such surrogate is reduction of uncertainty. The presumption is that an investigation program leading to a large uncertainty reduction has a larger value than a program with less reduction. This approach implies that cost-issues are not addressed at all; it more or less resembles a traditional uncertainty analysis (Level 1 in Fig. 1). Both Levels 1 and 2 are demonstrated in this paper.

2.3. Value of information analysis

The VOIA is performed in three steps. First, in "prior analysis", the statistical parameters and their associated uncertainties are estimated, based on present state of knowledge. Next, in "preposterior analysis", the statistical parameters and their associated uncertainties are estimated, based on the expected outcome of each investigation program, but *before* any investigations are carried out. Finally, the value of information is calculated for each investigation program. The calculated value of information can be used to identify the most efficient investigation program.