QUALITY ASPECTS OF DETERMINING KEY ROCK PARAMETERS FOR THE DESIGN AND PERFORMANCE ASSESSMENT OF A REPOSITORY FOR SPENT NUCLEAR FUEL

Presented at Métrologie 2007 Congress, Lille (FR), 18 – 21 June 2007

B. Adl-Zarrabi[1], R Christiasson[2], R Emardson[1], L Jacobsson[1], L R Pendrill[1], M Sandström[1], B. Schouenborg[1]

[1]SP Technical Research Institute of Sweden, Box 857, SE-50115 Borås, Sweden

[2]SKB Swedish Nuclear Fuel and Waste Management Co., Box 5864, SE-102 40 Stockholm

Leslie.pendrill@sp.se

Abstract

Aspects de qualité dans la détermination des paramètres principaux de roche pour la conception et l'évaluation d'exécution d'un dépôt pour le carburant nucléaire usé.

In planning for the appropriate disposal of radioactive waste, it is necessary to understand and predict the long-term changes that take place in a final waste repository and how these changes can influence the repository's ability to maintain adequate isolation of the spent nuclear fuel. The value of performing detailed measurement system analyses and interlaboratory comparisons as important means of providing confidence in test results is demonstrated for two key mechanical and thermal bedrock parameters. Systematic measurement quality assurance makes it possible to identify the degree the variations in measurement data depend on actual natural variability in the rock mass as opposed to uncertainties from the laboratory testing.

Introduction

The mechanical (compressive and shear strength, elasticity modulus, etc) and thermal (expansion coefficients, thermal conductivity, etc) properties of the bedrock are crucial parameters for the construction and long-term safety of underground repositories for spent nuclear fuel [1]. These mechanical properties are, together with rock stress measurements, initially used for a safe construction phase. In the early post-closure phase (up to 1000 years), the thermal properties become equally important and are, together with the mechanical properties, important when assessing the coupled thermo-mechanical processes that are expected to affect the repository.

The practical use of all test results is dependent on a correct treatment of measurement quality, particularly metrological traceability and measurement uncertainty. Estimations of test uncertainty will include a statistical analysis of repeated measurements of rock properties and a total measurement system analysis, covering the instrument used, the operator, chosen test method, environmental conditions and even the test objects themselves. In estimating these uncertainties, the test engineer's experience is used together with regular evaluation of measurement method accuracy through inter-laboratory experiments, see ISO 5725 [2]. Account has also to be taken of core sampling on site and questions of statistical representativeness. A second aspect of quality-assured measurements covers the actual mechanical strains and stresses and thermal gradients to which the rock is submitted underground on site.

The final step is to combine the measurement data on rock properties and compare the values of the different parameters with tolerance values for these, such as specified based on detailed, three-dimensional simulations of the site. Important steps include the correct treatment of measurement uncertainty when making decision of conformity assessment as well as realistic estimates of the risks and costs of incorrect decisions.

The paper will present examples of measurement quality assurance, system analysis and conformity assessment applied to rock mechanics and nuclear waste disposal.

Reliability of data used in analysis

Uncertainty in problem assessment can arise from many factors [3]. These could comprise both the conceptual uncertainty in understanding the problem, including the impact on analysis results of various simplifications made when the problem description is established, as well as the uncertainty in the data used. Geoscientific analyses additionally focus on all of the general geostatistical issues.

Uncertainty in data depends primarily on three factors;

- How typical are the data for the actual geological formation? This deals with issues such as geological homogeneity/heterogeneity and spatial variability, for example trends with depth
- The strategy for collecting representative samples, and the samples needed for the problem analyse.
- The quality of the data collected.

Two examples are discussed that are relevant for the design of a nuclear facility in a geological environment, illustrating how the assessment of data uncertainty can contribute to the improvement of confidence in the prediction outcome.

Example # 1, Influence of UCS on the analysis of stress-induced spalling

The problem of stress-induced spalling on an underground opening has been assessed by many authors. Martin [1999] has proposed an empirical relation based on the maximum tangential stress at the opening, σ_T and the uniaxial compressive stress, *UCS* at which spalling would occur:

$$\sigma_T/UCS \geq 0.55 \pm 0.20 \qquad (1)$$

The uncertainty in σ_T depends on how the geometry of the opening influences stress concentrations at the contour of the opening, but the largest uncertainty is related to estimation of the in-situ state of stress. This need for high quality stress estimation has been highlighted by for example Christiansson & Hudson [2003]. Generally speaking, the problem of an adequate determination of the state of stress at large depth is greater than the determination of the *UCS*, but the discussion in this paper is limited to the latter.

Example # 2, Influence of thermal conductivity on the canister spacing in a KBS-3 repositor

Heat generation from the spent fuel causes a temperature gradient from the deposited canister. The transfer of heat from the canister depends on the thermal properties of the buffer and the rock, as well as the dimensions of the deposition hole and the buffer. For the Swedish reference case with a heat generation of 1 700 W/canister and assumptions on the parameters such as density and water content that determine the thermal properties of the buffer, Hökmark and Fält [2003] calculated how the canister spacing depends on the thermal conductivity of the rock, highlighting the impact of uncertainty in the thermal conductivity on the estimation on how large the repository should be.

Measurement quality assurance

Measurement quality and reliability in the competence of laboratories making the tests can be assessed and assured with both internal and external measures.

- Internal means of quality assurance are e.g. use of reference material, control charts, regular internal audits etc.
- External means are on the one hand the surveillance audits e.g. within the legal authorisation/notification or accreditation procedure and on the other hand participation in inter laboratory comparisons of results of the same test item.

A key observation about measurement quality assurance is that the **test object** occupies a special place in the measurement system since it is both the entity whose intrinsic characteristics are to be determined as the prime aim of the test, but is at the same time an integral part of the measurement system. It will be important to distinguish between situations where:

- on the one hand the aim of the test is in fact to evaluate how, for instance, the object is affected by its environment or how much the object varies, and
- on the other hand, where uncontrolled environmental effects on the test sample lead to measurement uncertainty.

The test object is crystalline rock, which causes additional concerns [4] since geological heterogeneities cause natural variations in the mechanical and thermal properties. In addition, the mechanical properties may be affected by the stress paths the object has been subject to when it has been cored out from depth in the bedrock. The stresses depend both on the induced stresses and heat generation during core drilling, as well as the stress relaxation caused by the release of the core from its in-situ state of stress. The overall strategy in sample selection for testing in the SKB site investigation programme is based on:

- Consultation with site geologists on the representativeness of potential test objects.
- Collection of samples in bathes at a depth with a number of specimens as close to each other as practically achievable.

In addition, the results have to be critically reviewed. Especially test results that are anomalous compared to the majority of results from a batch have to be scrutinized. Local heterogeneities may have large influences on test results because of the small volume of rock involved in the testing methods.

The steps in evaluating measurement quality will be exemplified for two examples of measurement of critical properties of bedrock samples taken from proposed SKB site investigations for deep geological disposal of radioactive waste [5]. The particular rock determinations exemplified here are the uniaxial compressive strength test and thermal conductivity determined according to the TPS-method.

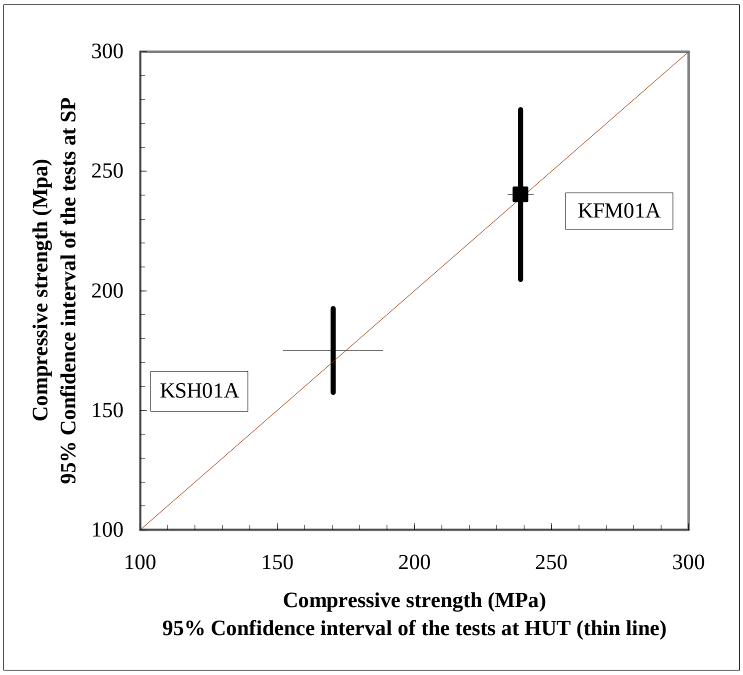

Fig. 1 Combined results of the uniaxial compressive strength tests.

Actual measurements I: Uniaxial compression test

The uniaxial compression test consists of the loading of cylindrical specimens in the axial direction up to and beyond failure (post-failure) in the actual tests [6]. The stress, axial and radial strains are recorded during the test and the elasticity parameters, Young's modulus and Poisson ratio as well as the uniaxial compressive strength are deduced from the measured sets of data.

Inter-laboratory experiment [7]

Determinations of uniaxial compressive strength of the bedrock samples were made at two testing laboratories: the Swedish National Testing Institute (SP) and the Helsinki University of Technology (HUT). Both laboratories tested the samples following the same standard. The main differences between the laboratories were the use of different test machines and different types of equipment for measuring the axial and radial deformations.

Detailed information about the samples and tests is given in the P-reports for example [8].

Figure 1 shows the mean values of the measurements at each laboratory plotted against each other. The 95 % confidence intervals are shown in the figure as vertical and horizontal lines for SP and HUT respectively.

The diagonal line illustrates where the cross should be if the results were identical. From the figure, we can see that the confidence intervals include the diagonal "zero-line". Hence, with 95% confidence, we can conclude that the combined systematic difference between the batches at the two laboratories and the systematic differences in methods and equipment is smaller than the scatter between the samples at each laboratory.

Actual measurements II: Thermal conductivity test

The determination of the thermal properties (thermal conductivity, thermal diffusivity and volumetric heat capacity) is based on a direct measurement method, the so called "Transient Plane Source Method » [9]

Interlaboratory experiment

The samples were first tested at SP and then at the Hot Disk AB laboratory. Figure 2 shows the mean results for thermal conductivity for the two lots of samples, with three different temperatures for each lot. The mean values of the measurements at each laboratory plotted against each other. The 95 % confidence intervals are shown in the figure as vertical and horizontal lines for HD and SP respectively. The diagonal line illustrates where the cross should be if the results were identical. From the figure, we can see that the confidence intervals in about half of the cases include the diagonal "zero-line". Hence, systematic difference between the batches at the two laboratories and the systematic differences in methods and equipment are more significant than the scatter between the samples at each laboratory in contrast to the measurements of the *UCS*.

However, care should be exercised in making due allowance for other sources of measurement error: Both laboratories have used nominally the same TPS method. Hence, additional systematic components to the measurement error may exist without being apparent in the interlaboratory comparison.

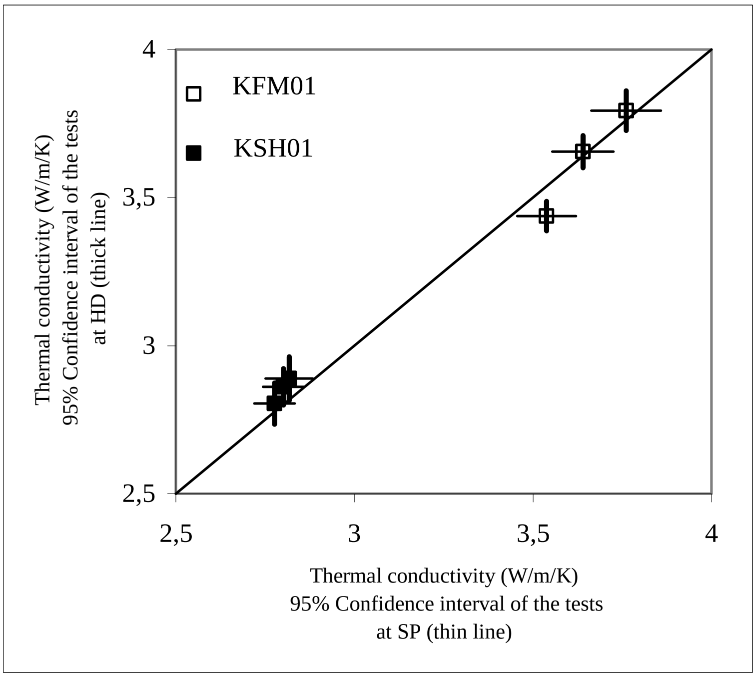

Fig. 2. Diagram showing the measurements of thermal conductivity

Discussion

The scatter in a set of laboratory data is dependent on many factors but can be simplified to the following relation:

$$\sigma_y^2 = \sigma_m^2 + \sigma_w^2 \qquad (1)$$

where σ_y^2 is the total scatter in a set of data, σ_m^2 is the natural variation amongst the tested specimens [10], and σ_w^2 is the total [11] variation due to the testing procedures, i.e., the measurement noise.

Estimation of natural variability and Uncertainties in testing

Based on the results of the interlaboratory tests, we can deduce information on the measurement noise in the two test cases UCS and TPS and for the different laboratories involved. The natural variation among the samples can be written as a function of the variances of the sum and difference of the measured signals

$$\sigma_m^2 = \frac{1}{4}\left(\sigma_{sum}^2 + \sigma_{diff}^2\right) \qquad (2)$$

and the measurement noise can then be found for the two laboratories as

$$\sigma_w^2 = \sigma_y^2 - \sigma_m^2 \qquad (3)$$

For the KSH site the measurement noise in the UCS measurements is typically 11-12 MPa. For the Forsmark site, it is difficult to draw conclusions about the measurement noise due to the large discrepancy in the results.

In the TPS measurements, the measurement noise is approximately 0 and 0.02 W/m/K for the SP and HD laboratories respectively at the KSH site and 0.08 W/m/K and 0 for the SP and HD laboratories respectively at the Forsmark site. Based on these results, it is reasonable to assume that the measurement noise in the TPS measurements is approximately 0.05 W/m/K.

The above analysis and conclusions about the measurement uncertainties at the different laboratories would not have been possible to perform without the interlaboratory comparisons. Additional labs in such comparisons would presumably help in the determination of measurements uncertainties especially for the USC measurements where we at present have difficulties in separating the effects due to the fact that the samples at the labs are different.

The two Swedish study sites enclose some 5 – 8 km^2 in the focused area for a tentative repository. The investigated depth is down to 1 000 m with a target depth in the interval 400 – 700 m. In addition, there are investigations carried out also outside the focus area to study the boundary conditions at each of the sites. It is obvious that there is the need for a strategy for investigating and sampling that has to focus on geological characterizations. These works divide the rock mass into domains that are estimated to be homogeneous. The sampling for characterization is focused on collecting batches of data in clusters at different locations and depths. The main purposes are to investigate how the natural variation of design parameters may vary in the scale of a tunnel (approximately sampling within a 2 – 5 m borehole length) and how consistent this natural variation is over the site, and with depth.

The amount of testing is a trade-off between the general geological understanding of the homogeneity/heterogeneity of a site, and cost. It is not realistic to establish a specific level of confidence in data to be achieved. Instead, by step-wise analyses of data, feed-back can be given to the data collection activities. Many of the issues that are studied, such as for example the risk for spalling of a deposition hole, have limited value where stability problems may be expected. It is relatively straight-forward to identify if a range of a parameter value for a geological domain may be of concern or not. So if for example the in-situ stresses are estimated to be large, it may be more important also to define the most likely range of UCS for the actual rock mass. In the Forsmark example the estimated state of stress has been estimated to be relatively high [SKB 2005 = SDM v1.2]. Spalling has been a concern that has been subject to special studies [Martin, 2005]. Even though the uncertainty of estimating the state of stress has the largest impact on the estimated risk of spalling, even a reduction of the uncertainty span of the UCS mean value in accordance to Table 1 is important in improving confidence in the prediction outcome.

Table 1 summarizes the uncertainties in the testing procedures and the natural variability of the samples. In the table, we present a standard deviation in all data for the gneiss granite in Forsmark according to SKB 2006 [SDM 2.1]. The standard deviation of the measurement noise is taken from (3) and discussed above. Assuming that the all measurements in the larger study are subject to measurement noise of the same size as reported in this paper, we can estimate the natural variability of this data set from (1).

Table 1 Uncertainties in testing procedures and natural variability of rock samples

	Variability *UCS* (MPa)	Variability *TPS* (W/m·K)
Larger Population	29	0.17
Measurement noise from (3)	12	0.05
Natural variability from (1)	26	0.16
Natural variation as percentage of mean value	9%	4%

In the present case, the strategy for sampling and laboratory testing seems to be adequate for the characterization of the mechanical and thermal properties of the bedrock. It remains to be evaluated if the actual strategy would be sufficient also in a more heterogeneous rock mass. It must also be considered that the sampling strategy has to be defined from the purpose with the project and the need of confidence in predictions.

Conclusions

The paper has illustrated the value of performing detailed **measurement system analyses** and interlaboratory **comparisons** as important means of providing confidence in test results for two key mechanical and thermal bedrock parameters. A well-functioning system of interlaboratory comparisons in all fields and at different levels may support the wider acceptance of test results. Furthermore, frequent participation in interlaboratory comparisons may result in a collective learning effect, leading hopefully to the results of the different laboratories converging successively and uncertainties getting smaller. It is important that in all the different fields regular interlaboratory comparisons are made available in view of overall improvement of measurement this brings.

It has been emphasised that it is advantageous to give a clear separation between **intrinsic object characteristics** – such as for instance actual heterogeneity – and an apparent heterogeneity arising from investigation with a particular measurement system. This separation is necessary both in assessing uncertainties as well in deducing the result of the test. The test objects in the present investigations were cores obtained from the drilling of bore hole. Therefore, the properties of the test objects vary, depending on variation of the petrographic composition, structure etc.

Account has also to be taken of **core sampling on site** and questions of statistical representativeness arise. The testing of geological materials such as crystalline rock requires a systematic strategy for sample selection to reduce the effect of natural heterogeneities. In addition, the stress paths the specimen may have experienced from its release from the bedrock may also influence the results.

- The strategy for sampling and testing of the mechanical and thermal properties in the Swedish ongoing site investigations for a nuclear disposal facility has been focused on batches of tests within short distances along the boreholes. This has revealed the extent of the natural variability in the rock mass on a scale that is relevant for the planned tunnels (up to approximately 5 m).
- All data from several boreholes has been used to assess the natural variation in the rock mass.
- Systematic assurance of measurement quality has made it possible to sort out to what extent the scattering in data depends on natural variability in the rock mass, as opposed to the sum of all uncertainties associated with the laboratory testing.
- It is crucial that the test methods are properly defined; systematic quality procedures are followed and that the operators and the laboratories are experienced.
- In the examples given in this paper, it has been shown how the systematic assessment of measurement uncertainties helps to determine the natural variability in rock properties.

References

1. B. Adl-Zarrabi, R Christiansson, R Emardson, L Jacobsson, L R Pendrill, M Sandström, B. Schouenborg 2007, “Quality aspects of determining key rock parameters for the design and performance assessment of a repository for spent nuclear fuel”, *in manuscript*.
2. ISO 5725 1994 "Accuracy (trueness and precision) of measurement methods and results"
3. J Helton *et al.* 2006 “Survey of sampling-based methods for uncertainty and sensitivity analysis”, *Reliability Engineering and System Safety* **91**, 1175 – 1209
4. SKB site description models (platsbeskrivande modeller) Forsmark and Laxemar, SKB 2005 and 2006.
5. SKB, 2001, Site investigations. Investigation methods and general performance procedure (Platsundersökningar. Undersökningsmetoder och generellt genomförandeprogram), SKB R-01-10, Svensk Kärnbränslehantering AB
6. ISRM 1999 “Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression”, *Int J Rock Mech Min Sci* **36**(3), 279 – 289.
7. Matz Sandström, SP Swedish National Testing and Research Institute, Forsmark and Oskarshamn site investigation Boreholes KFM01A and KSH01A: Inter-laboratory comparison of rock mechanics testing results, SKB P-report, P-05-239, December 2005, ISSN 1651-4416
8. Jacobsson, Lars, SP Swedish National Testing and Research Institute, Forsmark site investigation, Borehole KFM01A, Uniaxial compression test of intact rock, SKB P-report, P-04-223, December 2004, ISSN 1651-4416
9. Adl-Zarrabi, Bijan, SP Swedish National Testing and Research Institute, Forsmark site investigation, Drill hole KFM01A, Thermal properties: heat conductivity, and heat capacity determined using the TPS method and Mineralogical composition by modal analysis, December 2004, P-report, P-04-159, ISSN 1651-4416
10. Kurfürst *et al.* 2004 “Estimation of measurement uncertainty by the budget approach for heavy metal content in soils under different land use”, *Accred. Qual. Assur.* **9**, 64 – 75
11. Ramsey M H 2004 “When is sampling part of the measurement process?”,*Accred. Qual. Assur*. **9**, 727 - 8