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Searching for Indicators of Excavation Damage Using R Statistics Environment

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Abstract

Understanding the formation and physical characteristics of excavation damage of rock mass is critical for the long-term safety evaluation of deep geological disposal of spent nuclear fuel. In order to develop methods for identifying Excavation Damaged Zone (EDZ), physical and mechanical properties of 132 rock specimens were measured. All together 32 physical properties were measured, of which P- and S-wave velocity in three orthogonal directions and under six levels of axial loading. Derived properties were then calculated from the measured ones, leading to a total of 277 different properties, when accounting for measurement direction and level of axial loading. Considering that not all properties were measured from all specimens, this led to approximately 30 000 combinations of physical properties to shift through. Using R as a tool for the statistical analysis allowed the treatment of the entire dataset in reasonable time, thus providing a screening of existing correlations between different properties of the rock specimens. Furthermore, detailed interpretation could then be focused only on associations of statistical significance, whether or not this was apparent from the data. Best indicators for excavation damage based on this study appear to be electrical resistivity, S-wave velocity, shear impedance, shear modulus and Young's modulus.

Keywords

Excavation damage, petrophysics, rock strength, dynamic elastic parameters, static elastic parameters, laboratory testing, statistical analysis, R

Introduction

The main goal of the study was to identify anomalous physical properties linked to either increased porosity or abnormally low mechanical strength, indicative of excavation induced damage or natural defects in the rock mass. The secondary goal was to find associations between dynamic and static elastic properties, or static elastic properties and other physical properties. A site-specific model could then be used to estimate mechanical properties of the rock mass based on fast and cost-effective non-destructive geophysical methods.

All together 32 physical properties were determined, from which various derived properties were then calculated, leading to a total of 277 measured properties, accounting for direction and level of axial loading. Considering that not all properties were measured from all specimens, this led to approximately 30 000 combinations of physical properties to shift through with a total of approximately 800 000 data points. Inspecting such a volume of data manually was not feasible given the schedule, and an automated pre-screening process was developed using the R statistics environment. R is a high-level language/environment somewhat similar to MATLAB but developed for statistical computing and graphics as a GNU project (The R Foundation, 2017). It provides tools for statistical analysis and high-quality plotting, is fully customisable and freely available under the Free Software Foundation’s GNU General Public License (The R Foundation, 2017).

Specimens and experiments

Measurements focusing on petrophysical properties were carried out on 80 specimens from 12 drill cores in an investigation drift, containing veined gneiss (VGN, 39 pcs, 49 %), diatexitic gneiss (DGN, 13 pcs, 16 %) and granitic pegmatoid (PGR, 28 pcs, 35 %). For all specimens, density, porosity, magnetic susceptibility, remanent magnetisation, electrical resistivity at three frequencies (0.1 Hz, 10 Hz and 500 Hz), relative permittivity and P-wave velocity were measured. 20 of the most representative specimens were selected for S-wave velocity testing (referred to as Set 1a, while the other 60 specimens are referred to as Set 1b). Selection was based on 1) geological representativeness of the rock types, 2) how uniform a sequence the specimens create, and 3) proximity of the shallowest specimen in a sequence to the tunnel floor.

Mechanical testing was carried out on 52 specimens from 14 drill cores from the same investigation drift, containing veined gneiss (20+20 pcs, 77 %) in varying foliation orientations and granitic pegmatoid (6+6 pcs, 23 %). Of these specimens, 26 (referred to as Set 2a) were subjected to Brazilian test, and density, porosity, magnetic properties, electrical resistivity, relative permittivity and P-wave velocity were measured. The other 26 specimens (referred to as Set 2b) were subjected to uniaxial compressive strength (UCS) testing, and density, porosity, relative permittivity and P- and S-wave velocities under six levels of axial loading between 0.5 MPa and 20 MPa were determined. Various physical properties were calculated from the measured ones, including IP estimates, theoretical radar velocity and dynamic elastic parameters. From the UCS data, uniaxial compressive strength, crack initiation stress and crack damage stress levels, Poisson’s ratio and Young’s modulus were determined, and other static elastic parameters estimated. A summary of the tested properties by specimen set is shown in Table 1.

Table 1: *Tested and calculated properties per set.*

	Set 1		Set 2	
PROPERTIES MEASURED	**1a**	**1b**	**2a**	**2b**
Density	X	X	X	X
Porosity	X	X	X	X
Magnetic susceptibility	X	X	X	
Remanent magnetisation	X	X	X	
Electrical resistivity, $R_{0.1}$, R_{10} and R_{500}*	X	X	X	
Relative permittivity	X	X	X	X
P-wave velocity, unloaded	X	X	X	X
S-wave velocity, unloaded	X			X
P- and S-wave velocities, loaded				X
Crack initiation stress				X
Crack damage stress				X
Uniaxial compressive strength				X
Poisson's ratio (from UCS)				X
Young's modulus (from UCS)				X
Tensile strength			X	

*R0.1 is measurement at 0.1 Hz, R10 at 10 Hz and R500 at 500 Hz

**PL and PT values corresponding to resistivities at frequencies 0.1 Hz, 10 Hz and 500 Hz

***"Elastic parameters" means the combination of P/S ratio, Acoustic impedance, Shear impedance, Poisson impedance, Poisson's ratio, Lame's first parameters, Shear modulus, P-wave modulus, Bulk modulus and Young's modulus

	Set 1		Set 2	
PROPERTIES CALCULATED	**1a**	**1b**	**2a**	**2b**
Q-ratio	X	X	X	
IP estimates, PL and PT**	X	X	X	
Theoretical radar velocity	X	X	X	X
P/S-ratio, unloaded	X			X
Acoustic impedance, unloaded	X	X	X	X
Shear impedance, unloaded	X			X
Poisson impedance, unloaded	X			X
Poisson's ratio, unloaded	X			X
Lame's first parameter, unloaded	X			X
Shear modulus, unloaded	X			X
P-wave modulus, unloaded	X	X	X	X
Bulk modulus, unloaded	X			X
Young's modulus, unloaded	X			X
Elastic parameters***, loaded				X
Elastic parameters***, from UCS				X
P- and S-wave velocities, from UCS				X
CI/UCS –ratio				X
CD/UCS –ratio				X

Statistical analysis

Statistical analysis of the gathered data was divided into two main categories: descriptive statistics and related visualisation, and association analysis. Descriptive statistics were determined for all 277 measured quantities, additionally separated by rock type, depth and location. Minimum, maximum, median and first and third quartile were plotted as boxplots, while mean, standard deviation and interquartile distance (IQR) were recorded for further reference. Calculation was automated in the R environment and used the standard algorithms *min*, *max*, *quantile*, *median* and *sd*. The boxplots were visually inspected to identify differences between samples from different depths in order to distinguish the excavation damaged zone (Figure 1).

In addition to the boxplots, scatter plots and kernel density estimates of the data were produced. Scatter plots were used to compare current data with previous values and thus validate the experimental setup. Anomalies within the current dataset could be identified from scatter plots of the current data (Figure 2), which could be linked to visually observed EDZ features (Figure 3). More subtle anomalies could be identified when overlaying the current dataset with previously observed distribution (Figure 4). Kernel density estimates were used to illustrate the shape of distributions and to compare samples in order to identify anomalies. Kernel density estimate resembles a histogram, but provides a seed ("kernel") at the actual location of each data point, instead of dividing the data into bins. This means that the resulting curve is smoother than a histogram and converges faster to the actual shape of the distribution. Probability densities were normalised so that the peak value is 1. Kernel used was the Epanechnikovian kernel, and the kernel bandwidth was chosen to match the standard deviation of the kernel. Calculations were done with the standard R algorithm *density.default* and plotting using the *ggplot2* package.

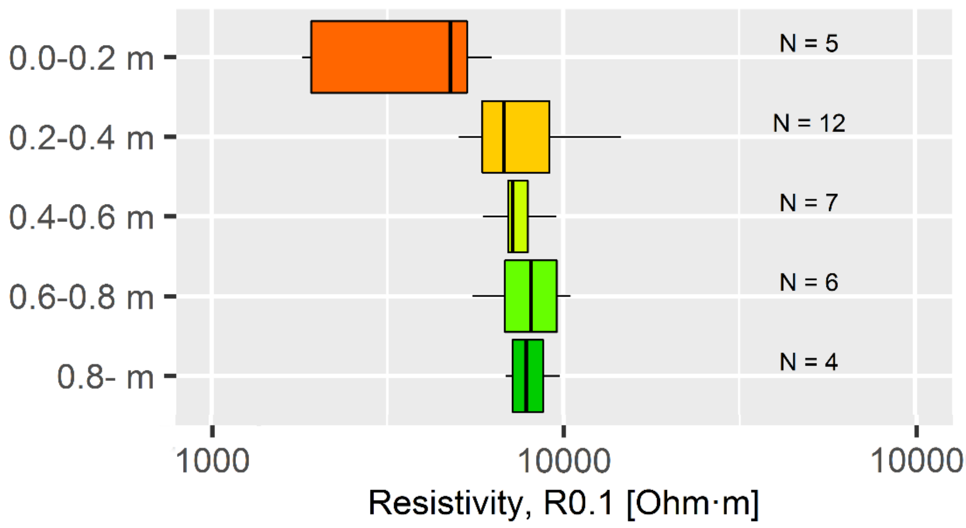

Figure 1: *Resistivity measured at 0.1 Hz for granitic pegmatoid specimens separated into groups by depth from the excavated tunnel surface. Box shows quartiles, spikes represent minimum and maximum. Sample size is given on the right. The top most layer shows up clearly anomalous, with lower resistivity and higher variation. Adapted from Kiuru (2017).*

Level of association between physical properties was tested by calculating Spearman rank correlation coefficients. The method is non-parametric, meaning it looks for a monotonic trend instead of linear dependency. This makes it less sensitive to outliers, and more suitable for use with complex or non-linear associations. Testing was done for all subsets (all data combined, separated by rock type, depth, location, level of loading etc.) regardless of whether any trends were expected to be visible.

From the calculated Spearman rho values, correlation matrices were formed for the various subsets. Trivial and known dependencies were removed from the matrices, and the remaining values were compared against corresponding critical Spearman rho values. Associations not exceeding the critical value were removed, leaving only statistically significant, unique, non-trivial associations.

Effort could then be focused on plotting and interpreting these associations. Due to the volume of data and interest of the study, plotting was further limited to depth from surface and porosity as explanatory variables, and to mechanical properties derived from the UCS and Brazilian tests as explained variables. Dynamic and static variants of a parameter were plotted against each other when applicable, regardless of the level of association. The resulting scatter plots were visually inspected and selected for interpretation if one of the following criteria was met: 1) the data showed a clear trend for the entire dataset or one of the rock types; or 2) the data showed shallow specimens as clearly anomalous. In addition, it was demanded that the data did not only separate rock types.

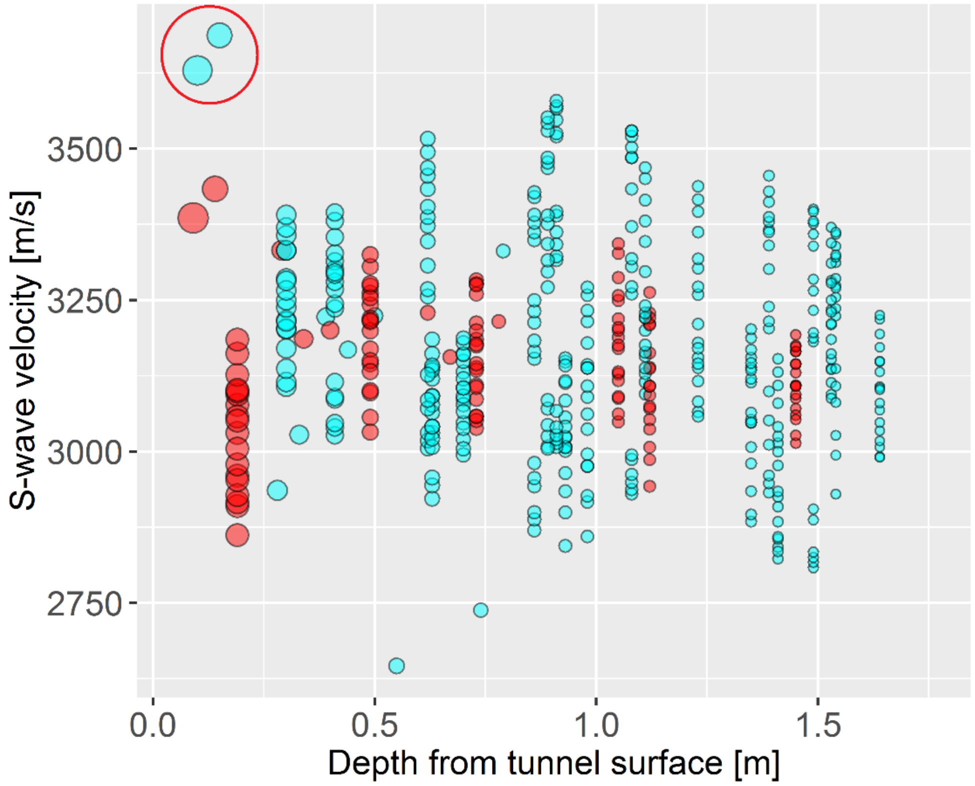

Figure 2: *S-velocity in respect to depth from the excavation surface. Light blue is VGN and red is PGR. Larger symbols represent specimens closer to the surface. Specimens EDZ109 and EDZ110 are marked with red circle and shown in Figure 3. Adapted from Kiuru (2017).*

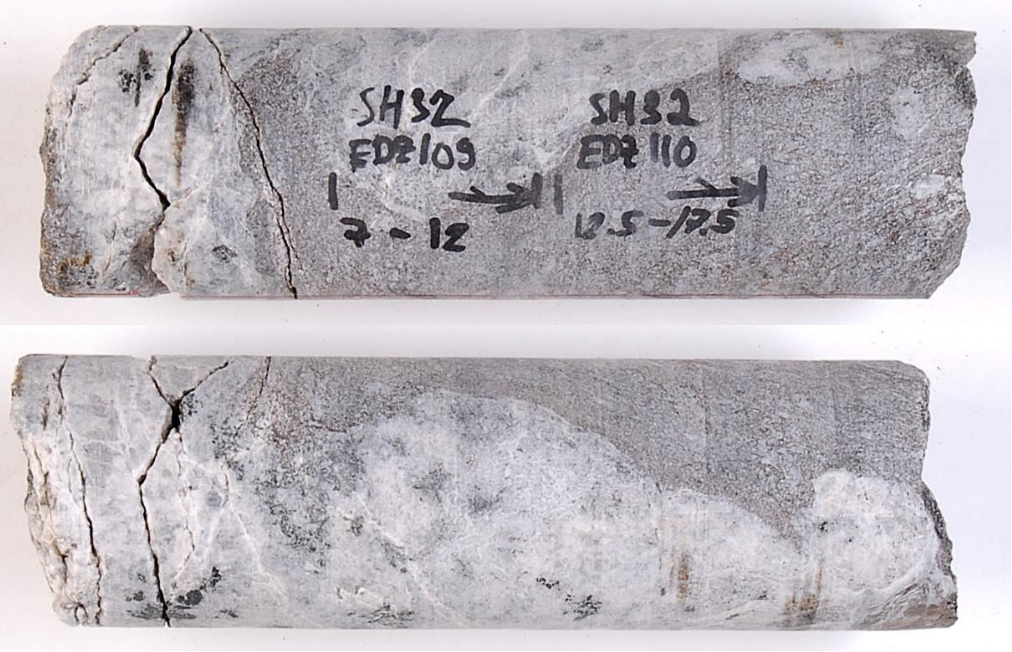

Figure 3: *Specimens EDZ109 and EDZ110 showing visible fracturing in the leucosome. The specimens appear as anomalous in plots of S-velocity (as shown in Figure 2), P/S –ratio, Poisson's ratio, shear impedance and Poisson impedance in respect to depth from the excavated surface. Adapted from Kiuru (2017).*

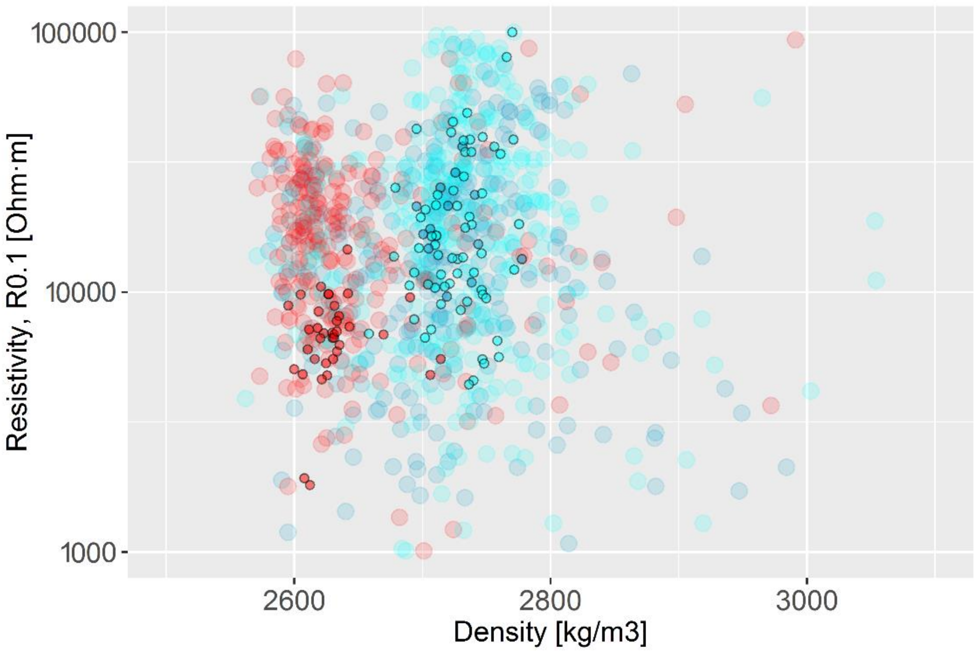

Figure 4: *Cross plot of density and resistivity. Previous data with larger mostly transparent symbols, current dataset with smaller opaque symbols. Resistivity values for PGR (red) plot at the lower end of the previously observed range, similar effect is not seen for gneissic specimens (VGN light blue and DGN darker blue). Adapted from Kiuru (2017).*

Conclusions

Using R as a tool for the statistical analysis allowed the treatment of the entire dataset in reasonable time, thus providing a screening of existing correlations between different properties of the rock specimens. Furthermore, detailed interpretation could then be focused only on associations of statistical significance, whether or not this was apparent from the data. Best indicators for excavation damage based on this study appear to be resistivity, S-wave velocity, shear impedance, shear modulus and Young's modulus.

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