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Effects of Excavation Damage on the Physical Properties of Rock Matrix

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Abstract. Posiva Oy has conducted investigations into excavation damage, including comprehensive laboratory testing of physical properties of rock specimens from excavation damaged rock mass. Laboratory testing was conducted on drill core specimens extracted from the excavated surface of a tunnel located at approximately 345 m depth in Olkiluoto, Finland. A total of 141 drill core specimens of three main rock types, a structurally isotropic coarse-grained pegmatoid (PGR) and structurally anisotropic veined gneiss (VGN) and diatexitic gneiss (DGN), were subjected to petrophysical testing, rock mechanics testing and petrographic analyses. Results from the various tests were subjected to rigorous statistical analysis in order to reveal the effects excavation damage has on the physical properties of the rock mass. Results of the study revealed changes that are credited to excavation damage in resistivity, S-wave velocity and various elastic properties of the rock specimens. Effects of excavation damage and the depth of the excavation damaged zone seem to be different to gneiss compared to pegmatoid. On microscopic level, the extent of excavation damaged zone appears to be 0.2 – 0.4 m depending on the measured property. This means that the deeper excavation damaged layer observed by geophysical surveys may be caused by larger scale fractures.

1. Introduction
Extent and properties of excavation damage and its possible effects on hydraulic conductivity are some of the key considerations when evaluating the long-term safety of the deep geological disposal of spent nuclear fuel [1]. Posiva Oy has conducted investigations into excavation damage over the past several decades, including comprehensive laboratory testing of a wide variety of physical properties of rock specimens from excavation damaged rock mass. These results have recently been published in a series of four Posiva Working Reports [2, 3, 4, 5].

2. Specimens and methods
Laboratory testing was conducted on drill core specimens extracted from the excavated surface of a tunnel located at approximately 345 m depth from ground surface in Olkiluoto, Finland. A total of 141 drill core specimens from 25 drillholes were subjected to petrophysical testing, rock mechanics testing and petrographic analyses. Specimens had three main rock types: a structurally isotropic coarse-grained pegmatoid (PGR) and structurally anisotropic veined gneiss (VGN) and diatexitic gneiss (DGN). Specimen depths from the excavated surface varied from 0 to 1.8 metres, as this was expected to fully capture the extent of major excavation damage as observed previously with geophysical methods [1].
Three sets of specimens were selected for the study: set 1 for petrophysical testing (80 pcs), set 2 for rock mechanics testing (52 pcs) and set 3 for saturation water salinity testing (9 pcs). Set 1 was divided into two subsets: all 80 specimens were subjected to basic petrophysical testing, and the most representative specimen series (20 pcs) were in addition subjected to S-wave velocity determination [2, 4]. Finally, 16 of the 20 most representative specimens were prepared for petrographic analysis and fracture network analysis [3]. Set 2 was also divided into two subsets: half were subjected to Brazilian test and the other half to UCS test [4]. Petrophysical measurements were done on set 2 specimens when it was possible considering the physical dimensions of the specimens. Set 3 specimens were tested using two saturation fluids (tap water and saline in situ) [2]. This study considers only the results obtained with tap water.

Measured properties included density and porosity; electrical, magnetic and electromagnetic properties; elastic wave velocities and elastic moduli (both static and dynamic); and microfracture network characteristics. Some of the measurements were conducted under various loading and saturation levels. Altogether, 32 physical properties were determined, which accounting for measurement direction and axial loading led to a total of 277 measured properties and approximately 800 000 data points. All specimens were prepared for the testing following the corresponding ISRM suggested methods and/or ASTM standards. All measurements were conducted on fully water saturated specimens. Details of the specimen sets and testing conducted are shown in table 1 [5].

| Specimen set | N (ALL) | N (PGR) | N (VGN) | N (DGN) | Testing conducted |
|--------------|---------|---------|---------|---------|------------------|
| Set 1a       | 20      | 10      | 10      | -       | D, M, E, P, S    |
| Set 1b       | 60      | 18      | 35      | 7       | D, M, E, P       |
| Set 2a       | 26      | 6       | 20      | -       | D, M, E, P, B    |
| Set 2b       | 26      | 6       | 20      | -       | D, E*, P, S, L, U|
| Set 3        | 9       | 3       | 6       | -       | D, M, E, P (saline) |

Petrographic analysis was performed to get a better understanding of the typical compositions of the two main rock types (PGR and VGN) [3]. Microfracture networks of the 16 set 1a specimens were analysed using 5 mm thick disks, cut perpendicular to the drillhole axis. These discs were impregnated with a UV fluorescent epoxy and polished, then photographed using an Olympus DP73 camera mounted on an Olympus BX41 microscope. The resulting images were processed using a trainable Weka segmentation plug-in for the ImageJ-based Fiji environment [6] to produce simplified binary images consisting only of fractures and host rock. Further processing of the resulting images was done in MATLAB [7] to extract the geometric properties of the fracture networks, which were later used as a basis for DFN modelling [3].

Results from the various tests were subjected to rigorous statistical analysis as a part of a larger context in order to reveal the effects excavation damage has on the physical properties of the rock mass. Results were analysed with respect to specimen depth from the excavated surface, while also taking into account the interdependencies observed between various properties and how the results compare to previous results from deep drillholes on site. Due to the volume of data, statistical analysis was partially automated and carried out in the R statistics environment, with manual inspection focusing on properties that showed unique, non-trivial associations exceeding the corresponding critical value of the Spearman rank correlation coefficient. [5]
3. Observed effects of excavation damage on the rock matrix

Results of the study revealed changes that are credited to excavation damage in resistivity, S-wave velocity and various elastic properties of the rock specimens [5]. Some of these changes were found to be different for the two main rock types (PGR and VGN).

There was a notable difference in resistivity between pegmatoid and gneiss observed in this study. This contradicts previous studies, which have shown that the resistivity distributions of Olkiluoto pegmatoids and veined and diatexitic gneisses are similar [9]. Porosity values of the pegmatoid and gneiss specimens did not differ significantly [2], thus the effect cannot be attributed to differences in porosity. When we look at the resistivity values with respect to true vertical depth (figure 1), we can see that the pegmatoids separate from the gneisses close to the excavated surface. Resistivity values of pegmatoids in the first 0.3 m are anomalously low. Furthermore, pegmatoids show increasing resistivity with increasing depth, a trend that is not observed for the gneisses. [2]

![Figure 1](image_url)

**Figure 1.** Resistivity with respect to specimen depth. Red is pegmatoid, light blue is veined gneiss, darker blue is diatexitic gneiss. Pegmatoid shows increasing resistivity with increasing depth. Gneiss does not show a similar effect.

As the observed differences in resistivities cannot be explained by fundamentally different resistivities or differences in the porosities of the specimens, it is likely that the observed differences are due to differences in the rock matrix, i.e., differences in the type of microfractures, such as their orientation and interconnectivity. This was supported by the analysed thin sections: fractures in gneiss were short and mostly in one preferred orientation, whereas fractures in pegmatoid were longer and had two preferred orientations [3].

S-wave velocity did not show a clear trend with depth but separated specific specimens with anomalously high values (figure 2). These were located near the surface in the first 0.2 m. Some of these specimens could be directly tied to visually observable excavation damage [2]. Several elastic parameters directly tied to S-wave velocity also separated the same specimens [2], e.g., dynamic Poisson’s ratio calculated based on P- and S-wave velocities (figure 3).
Figure 2. S-wave velocity with respect to specimen depth. Red is pegmatoid, light blue is veined gneiss, darker blue is diatexitic gneiss. Both rock types show anomalously high values in the first 0.2 m.

Figure 3. Dynamic Poisson’s ratio with respect to specimen depth. Red is pegmatoid, light blue is veined gneiss, darker blue is diatexitic gneiss. Both rock types show anomalously low values in the first 0.2 m.
Finally, we can look at the segmented images of the fracture networks. These sets of images span from approximately 0.1 m to 0.7 m from the excavated surface. For veined gneiss (figure 4) we can see a clear increase in the number of fractures in the first 0.3 – 0.4 m from the excavated surface (figure 4a-d). This suggests that excavation damage forms microscale fracturing in veined gneiss in the first 0.3 – 0.4 m. However, significant changes in porosity and resistivity are only observed for one of the images (figure 4c). This in turn suggests that the increased fracturing caused by the excavation damage is mainly formed by short fractures, that do not connect to allow an increase in the effective porosity or resistivity of the rock mass. Below 0.5 m from the surface, the rock mass seems to return to a baseline state of approximately 0.4 % porosity and 10 000 – 15 000 Ωm resistivity, which is consistent with previous studies [2, 9].

![Figure 4](image-url)

**Figure 4.** Series of segmented images extracted from the fluorescent images of veined gneiss specimens. Images are in order of increasing depth (a-f). Physical properties shown: D = depth, P = porosity, R = resistivity.
When we look at the pegmatoid (figure 5), we can see more pronounced and longer fractures in the first 0.3 – 0.4 m from the excavated surface (figure 5a-d). This suggests that in pegmatoid, excavation damage causes mainly formation of longer fractures controlled by, and formed at, natural grain boundaries. As these long fractures are better connected than the fractures formed in veined gneiss, a clear increase in porosity and decrease in the resistivity values can be observed close to the surface. The effect is most pronounced down to a depth of approximately 0.2 m (figure 5 a-b) but can be to approximately 0.6 m depth. Below that, the rock mass seems to return to a baseline state, which is again consistent with previous studies [2, 9].

Figure 5. Series of segmented images extracted from the fluorescent images of pegmatoid specimens. Images are in order of increasing depth (a-f). Physical properties shown: D = depth, P = porosity, R = resistivity.
4. Conclusions
Based on this study, the following observations were made:

- Changes that were credited to excavation damage were observed in resistivity, S-wave velocity and various elastic properties of the rock specimens.
- Resistivity values of pegmatoids were anomalously low in the first 0.3 m and increased with increasing depth. Similar effect was not observed for gneiss.
- S-wave velocity did not show a clear trend with depth but separated specific specimens with anomalously high values. These were located in the first 0.2 m. Same was true for a variety of dynamic elastic properties linked to S-wave velocity.
- Effects of excavation damage on the rock matrix and the depth of the excavation damaged zone seemed to be different to gneiss compared to pegmatoid.
- The extent of excavation damaged zone appeared to be 0.2 – 0.4 m depending on the measured property. This means that the deeper excavation damaged layer observed by geophysical surveys may be caused by larger scale fractures not present in the relatively intact laboratory specimens.
- Finally, it must be noted that these results are based on a limited data set, from a single location with highly heterogeneous rock mass, and that further research will be necessary to confirm the observations.

5. Disclaimer and conflicts of interest
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