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QUANTITATIVE DETERMINATION AND MONITORING OF WATER DISTRIBUTION IN ÄSPÖ GRANITE

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Abstract

To identify possible zones of two-phase-flow and the extension of the excavation disturbed zone, geoelectric measurements are conducted in the ZEDEX- and the DEMO-tunnel. The electric resistivity of a hard rock is usually determined by its water content, its water salinity and its porosity structure. By calibration measurements of the resistivity on rocks with well known water content, a relation between resistivity and water content for Äspö granite is determined. This relation is used to correlate the in-situ resistivity with the water content of the rock. To determine the in-situ resistivity between the ZEDEX- and the DEMO-tunnel an electrode array of nearly 300 electrodes was installed along the tunnel walls and in one borehole. With a semiautomatic recording unit which is operated by a telephone connection from the GRS-office in Braunschweig/Germany, the resistivity is monitored between and around the tunnels. To correlate the resistivity with the water content, the measured apparent resistivity has to be converted into a resistivity model of the underground. Since many thin water bearing fractures complicate this inversion process, the accuracy and resolution of the different inversion programs are checked before their application to the data. It was found that an acceptable quantitative reconstruction of the resistivity requires the integration of geometric information about the fracture zones into the inversion process. For a rough estimation of the position of possible fracture zones, a simple inversion without any geometric boundary conditions can be used.

Since the maximum investigation area is limited along a single tunnel for profile measurements, tomographic measurements were also applied to estimate the resistivity distribution between the ZEDEX- and the DEMO-tunnel. These tomographic measurements have a lower resolution than the profile measurements due to the required large computer power, but result in reconstructions that give an estimate of the resistivity distribution in this area without disturbing the rock or the hydraulic field. Although the extension of single water bearing fractures cannot be proved due to the low resolution, more regional variations, especially with time, are monitored very well.

1 Introduction

For the identification of zones with possible two-phase-flow, the knowledge of the water content of a rock is important. From the water content, the saturation can be estimated if the porosity is determined, too. For this purpose non-destructive methods have the advantage of leaving the hydraulic field undisturbed. Consequently, geoelectric methods are highly suitable for such a problem. The quantitative determination and monitoring of moisture distribution in low-porosity rocks with geoelectric resistivity methods has successfully been applied at the GRS-Braunschweig (former GSF-Braunschweig) since 1989. During the last years, the recording technique, the data processing and the interpretation were consequently improved which allows now the application of this technique to the difficult case of fractured rock.

2 The methodology of resistivity interpretation in fractured rock

The methods of in-situ resistivity mappings are well known and have not changed very much during the last years. Popular configurations like the Wenner layout or the dipole-dipole layout are still in use. But with the introduction of high performance computers it is possible to improve the interpretation of the measured resistivities.

From the measured current and voltage values an apparent resistivity is computed. In seismic methods the influence of the rock on the properties of the measured parameters, e.g. on velocity or attenuation, can be confined to a small tube connecting source and receiver, the seismic ray. In resistivity measurements a much larger area contributes to the computed resistivity value. For this reason, this value cannot be addressed to a single point although this is done for the visualisation of the data. For the interpretation a resistivity model of the underground is necessary. The computation of the true resistivity from the measured apparent resistivity is called inversion. Usually this inversion process was done by comparing the apparent resistivity with computed model curves which results in a 1-dimensional resistivity model.

During the last years, several programs for a 2-dimensional inversion of resistivities have become available. They differ in their concept of integrating geometric and topographic information. After the inversion, the resulting resistivity model of the underground can be interpreted in terms of petrophysical properties. In a common hard rock the water content presents the most important contribution to its resistivity. For each rock a specific relation between the water content and its electric resistivity exists. This relation is also influenced by the value and structure of its porosity. Once this relation is measured in the laboratory on samples with well known water contents, the inverted true resistivity distribution in the underground can be interpreted in terms of water content.

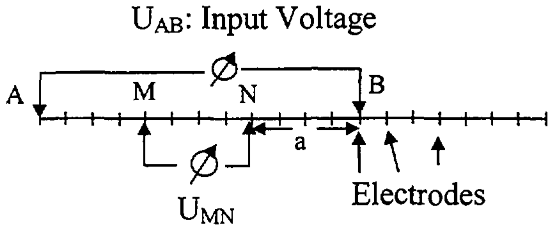
For such a quantitative interpretation, the reliability and accuracy of the used inversion programs have to be estimated.

2.1 Resistivity Mapping Using Wenner Configurations

Geoelectric mapping with the Wenner configuration (Fig.: 1a) is a well known geophysical method. In hard rocks such as granite, electrodes are cemented to the rock with a constant spacing. To measure the apparent resistivity of the rock, a known voltage is applied between two of these electrodes (A/B) inducing a current through the rock. As a result of this current, a voltage can be measured between two other electrodes (M/N). The spacing of the electrodes A-M-N-B is the configuration parameter a. From the induced current (I_{AB}) and the measured voltage (U_{MN}), an apparent resistivity can be calculated using equation (1).

$$\rho_a = 2 \cdot \pi \cdot a \cdot \frac{U_{MN}}{I_{AB}} \tag{1}$$

To correlate the resistivities with the water content of the rock, the apparent resistivities have to be inverted to yield the true resistivities. Only these true resistivities can be interpreted in terms of water content of the rock (figure 1b).



$$\rho_a = 2 \cdot \pi \cdot a \cdot \frac{U_{MN}}{I_{AB}}$$

ρ_a: Apparent Resistivity

I_{AB}: Input Current

U_{MN}: Measured Voltage

a: Configuration Parameter

Figure 1a: Wenner-Mapping configuration

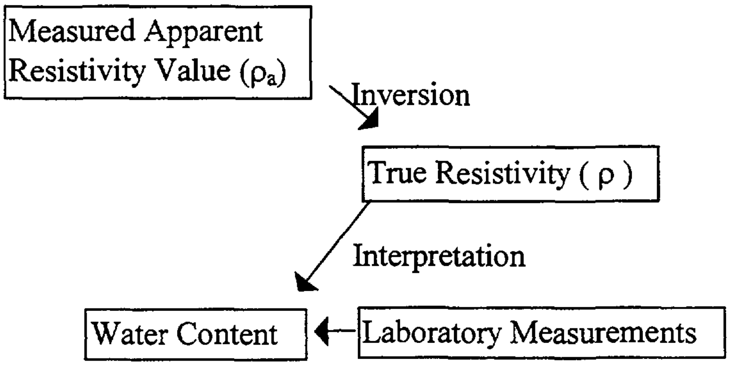


Fig. 1b: The methodology of geoelectric mapping, the processing and the interpretation of the measured values

2.2 2D-Inversion of Pseudosections

As a result of the resistivity mapping using the Wenner configurations, a distribution of apparent resistivities (ρ_a) for different layout parameters (a) and different mid points of the configuration (x) is obtained (Fig. 2). The visualisation of the measured apparent resistivities is called pseudosection. The distribution of the apparent resistivity values must not be interpreted in terms of water content because its only a rough estimate of the underlying petrophysical situation. For a quantitative interpretation this pseudosection has to be inverted.

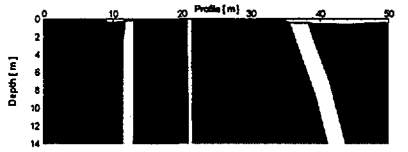


Fig.2a: Synthetic Resistivity Model

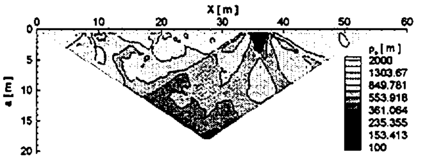


Fig. 2b: Apparent resistivities for a synthetic model with fractures

At the moment (1998), only a few commercial programs for a 2-dimensional inversion of resistivity pseudosections are available. For a 3D inversion no commercial software is available although some universities are working on this topic. The two applied programs differ in their ability to integrate geometric boundary conditions into the inversion process. But the basic principle is the same in both programs: from the measured apparent resistivities, a model of the resistivity distribution in the underground is estimated. For this model, the theoretical measurements are calculated and compared with the real measurements. The difference is used to improve the model. This iteration is continued until a satisfying adaptation is achieved.

2.2.1 Inversion Result With RES2DINV

The inversion program RES2DINV is not able to integrate geometric boundary conditions into the inversion process. On the other hand it does not need such information in advance for an inversion. The inversion result (Fig. 3) for the synthetic data set (Fig. 2b) shows clear anomalies of low resistivities at 12 m , 21 m and around 37 m which are the positions of the low resistivity bodies in the artificial model (Fig. 2a). But in contrast to figure 2, a the background of the model is not homogeneous. Many small anomalies of high resistivity occur near the surface. Additionally, it seems that the low resistivity anomalies are accompanied by a high resistivity anomaly nearby. This result shows that in an environment with elongated thin anomalies with a high resistivity contrast to the background the inversion result of the program RES2DINV should only be used as a qualitative estimate of the position of the anomalies.

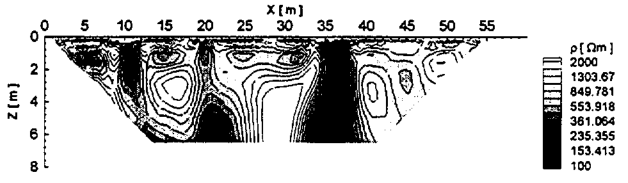


Fig. 3: Inversion (RES2DINV) result of the synthetic apparent resistivities

2.2.2 Inversion Result With RSXIP2DI

In contrast to the program RES2DINV, it is possible to integrate geometric boundary information into the program RSXIP2DI. An advantage of this method is that the degrees of freedom are reduced which simplifies the calculations. To get a satisfying adaptation of the values and a correct resistivity distribution of the underground, it is necessary to start with a good initial model. Especially the number and general positions of the different bodies are critical parameters of the model. Although it is possible to allow the program a variation not only of the resistivities but also of the position and shape of the bodies no additional body can be inserted during the inversion process.

In this example the smallest of the bodies, was (intentional) not integrated in the initial model. Consequently, the inversion result only tries to model two of the bodies. In the initial model all of the anomalies were perpendicular to the surface. The dip of the rightmost anomaly was only corrected up to a depth of approximately 4 m. This is an indication of the maximum depth of relevance of the model. With greater depths the resolution decreases and a very small anomaly like a water bearing fracture has only a minor impact on the measured resistivity values at the surface.

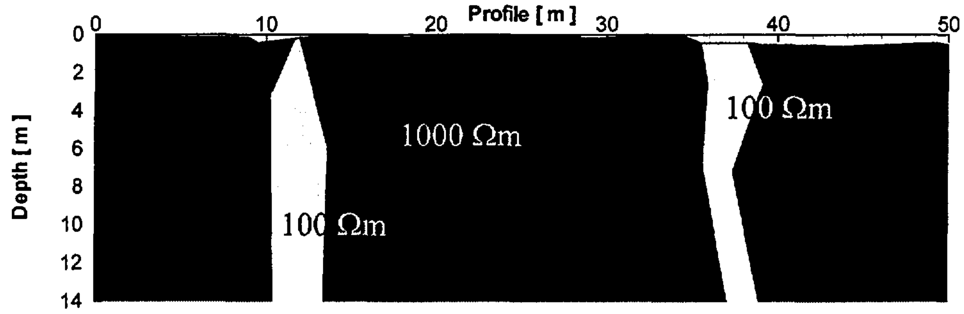


Fig. 4: Inversion (RSXIP2DI) result of the synthetic apparent resistivities

2.3 2D Inversion of Resistivity Tomograms

Since the profile measurements have only a small depth of investigation, tomographic measurements are used to estimate the more regional resistivity distribution between the ZEDEX- and the DEMO-tunnel. The principle of the resistance tomography differs slightly from the profile measurements. Between two electrodes a known voltage is applied. This voltage induces a potential field in the rock. This field is measured at other electrodes of the array. From many measurements with different positions of the input voltage, the resistivity distribution in the area surrounded by the electrodes can be computed. Since many such electrode configurations are possible in an array with nearly 300 single electrodes, model computations have been used to select the most expressive configurations. Computer power is the other limiting factor. With the actual software it is only possible to compute tomograms from arrays with 49 electrodes. For large areas, this lowers the resolution of the model. The electrode configurations used with the Äspö array are described in more detail in section 3.4.

2.4 Guidelines for Resistivity Interpretation in Fractured Rock

From the investigations on the resolution and accuracy of the different programs which are available some general guidelines for the application and interpretation of the resistivity method *in rock containing water bearing fractures* can be derived:

1. An inversion with the program RES2DINV should only be used as an estimate of the major resistivity structure.
2. Thin elongated anomalies with a high resistivity contrast produce a high **and** a low resistivity anomaly in the inversion result.
3. The resolution of profile measurements / inversions decreases with depth.
4. As much additional information as possible has to be integrated into the inversion process, e.g., number, position and shape of expected anomalies.
5. For a quantitative interpretation the fracture zones have to be modelled explicitly.

3 Quantitative Determination of Water Distribution in Äspö Granite

For a quantitative determination of the water distribution in the rock between the ZEDEX- and the DEMO-tunnel, an electrode array was installed. With this array and the described interpretation software, the resistivity distribution around and between the tunnels was determined. To correlate the electric resistivity with the water content of the rock, laboratory measurements were necessary. With the installed array, the automatic recording unit, the remote control from the GRS-office at Braunschweig / Germany, and the laboratory measurements a quantitative determination and monitoring of the water distribution in this area were possible.

3.1 Resistivity - Water Content Relation for Äspö Granite

For the quantitative determination of the water content in Äspö granite, the knowledge of the relation between resistivity and water content for this specific rock is necessary. This relation was measured in the laboratory on samples with known water content. The results are shown in figure 5.

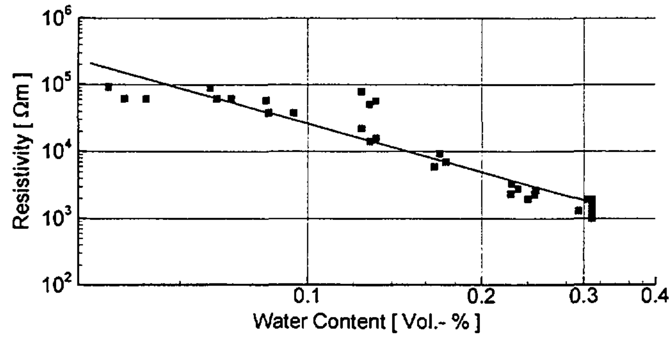


Fig. 5: Relation between water content and resistivity measured on Äspö granite samples with well known water content

3.2 Multi-Electrode Array at Äspö

For the determination of the resistivity and the water content between the ZEDEX- and DEMO-tunnel, 263 electrodes on 4 profiles were installed on the walls of the tunnels around this area; 111 electrodes in the ZEDEX drift, 42 and 10 electrodes in the access tunnel, and 100 electrodes in the DEMO-tunnel (Fig. 3). The electrodes on these profiles are 5-cm-long steel pins. They were cemented in small 3-cm-deep boreholes. The spacing between the electrodes was 0.5 m. To cover the fourth side of the area, another 36 electrodes were installed in a 40-m-long borehole. Since the borehole diameter is sufficient only for a limited number of cables, the distance between the electrodes is 1 m. All these electrodes are connected with a single cable to the automatic recording unit in a container at the end of the DEMO-tunnel which is controlled via a telephone line from the GRS-office in Braunschweig. The data were transferred via this telephone connection, too. This allows a high frequency of measurements. Although one reading lasts only 15 seconds, up to 8 hours are necessary to get a complete mapping of the ZEDEX or DEMO-tunnel. After some experiments it was found that the input voltage could be reduced to 50 V for all measurements.

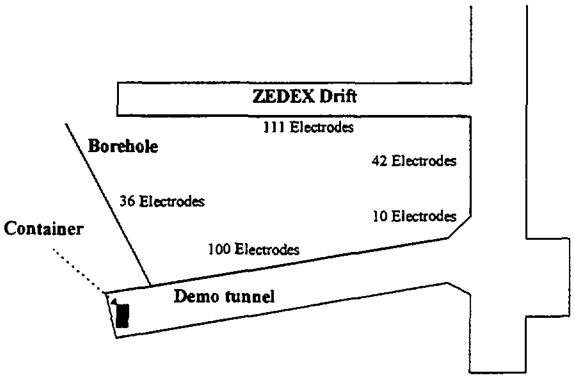


Fig. 6: Distribution of the electrodes around the ZEDEX- and the DEMO-tunnel

3.3 Results of Geoelectrical Mapping

The results of the geoelectric mappings presented here are only an example for a single data set from each tunnel. The results have been obtained by an interactive modelling of the fractures. These fractures can be observed on the walls of the tunnels.

3.3.1 Demonstration-Tunnel (K)

The results from the DEMO-tunnel show six different fracture zones (Fig. 7). The topography included in the model is only approximated but the exact measurements from the Äspö-survey department are now available and will be integrated in further interpretation. However, it is already shown that the maximum topography in the Äspö tunnels is not expected to have a significant influence on the inversion results.

The resistivity of the background rock in the model is about 1000 Ωm. According to the laboratory results, this correlates to a full saturation of the intact rock. In contrast to this background, the fracture zones are modelled with a much lower resistivity of less than 100 Ωm. A more precise reconstruction is difficult because of the extremely high resistivity contrast which is limited only to a very small area. A slight variation in one of these parameters has, at least near the surface, a great impact on the other parameters.

One of the modelled fracture zones (the fourth from the left) has a slightly higher resistivity than the others. This is an indication for less water and a lower extension of this zone. Since it is difficult to estimate the absolute error of the model in this situation a quantitative interpretation of the resistivity in the fracture zone in terms of water content does not seem possible at the moment.

Besides the resistivity in the fracture zones, it is remarkable that no additional layer near the surface is necessary to explain the measured data in this model. This is an indication for only a small or even not existing excavation disturbed zone. At least, the excavation disturbed zone is not as big as it was suggested by the inversion results from the RES2DINV program. This program has difficulties with the exact inversion of thin elongated anomalies which are perpendicular to the profile.

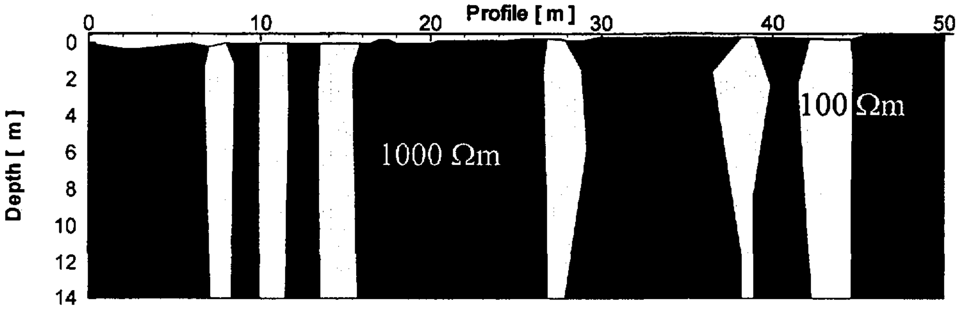


Fig. 7: Inversion result of the DEMO-tunnel profile measurements (06. Jan. 1998)

3.3.2 ZEDEX-Tunnel (Z)

The inversion results from the DEMO-tunnel are very similar to the results from the ZEDEX-tunnel. The resistivity of the background is around 1000 Ωm and the water bearing fracture zones which are obvious at the surface are modelled explicitly. In contrast to the DEMO-tunnel, however, it is necessary to model a body near the surface with slightly higher resistivity. The reason for this anomaly cannot be a hidden water bearing fracture zone since the anomaly is very shallow. This anomaly is an indication for an excavation disturbed zone.

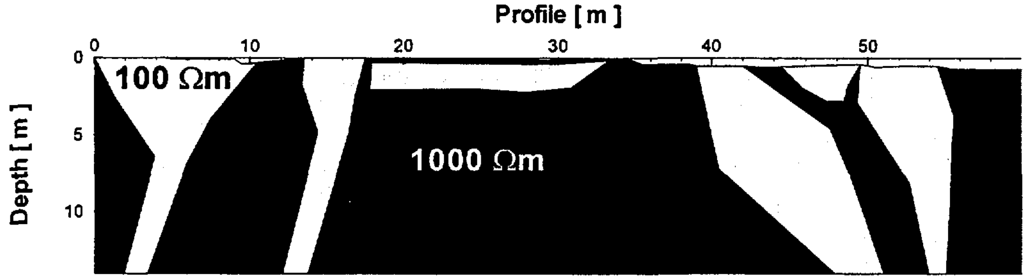


Fig. 8: Inversion result of the DEMO-tunnel profile measurements (06. Jan. 1998)

3.4 Resistivity Tomograms

For this method, the measuring configuration differs slightly from Wenner-mappings. The input electrodes (A, B) and the output electrodes (M, N) are arranged as single dipoles (Fig. 11). For a complete data set, the position of the input dipole (A, B) is fixed and the output dipole (M, N) is moved around the area to be investigated. Afterwards, the input dipole is moved to another position, and the measurements are repeated.

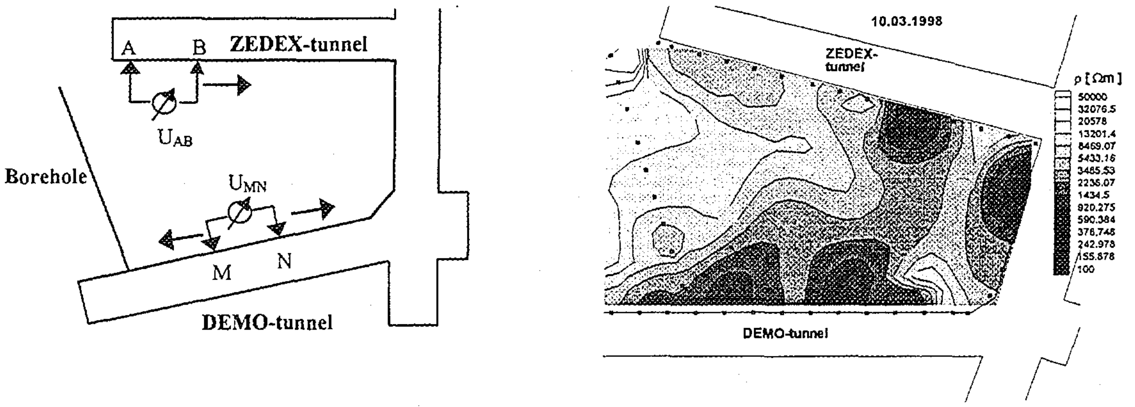


Fig. 9: Principle of dipole-dipole measurements and example of tomographic reconstruction.

Since a complete data set of all possible configurations from a multi-electrode array with 299 electrodes would exceed the capacity of the used inversion program, the number of configurations has to be reduced. In this case, model calculations have shown that a data set with 300 selected values should give a good estimate of the water content in the rock.

Since the capacity of the inversion software is limited to 49 electrodes, the resolution of the model is rather low with only 2 m x 2 m (Fig. 10). This is too low for an explicit modelling of the water bearing fractures in this area with an extension of only a few centimetres. But due to the large resistivity contrast they have an influence on the overall reconstruction of the resistivity distribution. Since the accuracy of the model is highest near the electrodes, the low resistivity anomalies in this part give an indication of the positions of the fracture zones. However, a proof for the connection of water bearing structures in this area is not possible with this resolution. Although the fractures can not be modelled explicitly, their changes in water content can be estimated by changes in the tomographic reconstruction with time.

4 Summary and Conclusion

Developments of the geoelectric instruments and the inversion software of resistivity measurements have improved the quantitative interpretation of the in-situ resistivity and related petrophysical parameters such as water content. Although a rock with water bearing fracture zones is still the limit for a justified quantitative interpretation, it is possible to get estimations of the water distribution in the rock with this method without disturbing the hydraulic field.

To obtain an optimum inversion of the measured data, an explicit modelling of water bearing fractures is necessary. For the special case of the Äspö geoelectric array, the topography along the tunnel walls is neglectable. Interpretations with the program RES2DINV imply additional positive anomalies besides water bearing fractures which lead to a wrong interpretation in terms of water content. With the program RSXIP2DI, these effects are eliminated by integrating the geometric boundary conditions. Indications for an excavation disturbed zone are found but, if existent, it is much smaller than predicted from RES2DINV inversions.