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Measurements of potential fields caused by earth currents and estimation of the bulk electric resistivity between deep boreholes at Forsmark

Hans Thunehed

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

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Measurements of potential fields caused by earth currents and estimation of the bulk electric resistivity between deep boreholes at Forsmark

Hans Thunehed, GeoVista AB

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Summary

Two types of measurements have been carried out in the Forsmark area. The electric potential has been mapped over an area above part of the planned deep repository for spent nuclear fuel. The electric potential has also been measured along two deep boreholes, KFM07A and KFM24. Electric resistivity measurements have been carried out as cross-hole measurements between KFM07A, KFM24 and HFM22. Measurements have also been carried out between one of the boreholes (KFM07A) and the surface.

The Fennoscan HVDC (High Voltage Direct Current) link between Sweden and Finland has a return electrode at Fågelsundet, around 25 km north of Forsmark. The link consists of two poles (Fennoscan 1 and 2) and unbalanced current between the two poles is transmitted to ground through the electrode. The electric potential measurements are correlated with the output current in the electrode at Fågelsundet The measured potentials were normalized by the current magnitude and are presented as a contour map for the surface data and as graphs for the borehole data. The results of the potential measurements are compatible with a conceptual model. The injection of current at the Fågelsundet electrode raises the electric potential at Forsmark causing electric current to flow through the grounded neutrals of the substation transformers. Current is then transferred from Forsmark via the phase conductors of the AC power lines. Current may also be transferred via the top conductor of the power line towers and a buried grounding cable that follow much of the power line paths. The grounding system of the substation will thus pick up current when current is injected at the HVDC electrode and vice versa. This will create a local potential field around the substation with rather large gradients.

All the resistivity measurements were merged to a common dataset. Inverse modelling was then carried out where a block model was estimated that could explain the measured data within specified error limits. The block model gives representative resistivity estimates at a length scale that is representative for e.g. modelling of corrosion rates in the planned repository. The resistivity at repository depth was estimated to around 5 000 Ωm between KFM07A and KFM24.

Sammanfattning

Två typer av geofysiska mätningar har genomförts vid Forsmark. Den elektriska potentialen har karterats över delar av det planerade slutförvaret för använt kärnbränsle. Den elektriska potentialen har också mätts upp längs två djupa borrhål, KFM07A och KFM24. Mätning av elektrisk resistivitet har utförts som mellanhålsmätning mellan KFM07A, KFM24 och HFM22. Dessutom har mätning utförts mellan KFM07A och markytan.

HVDC-länken (High Voltage Direct Current) Fennoskan har en returelektrod vid Fågelsundet, cirka 25 km norr om Forsmark. Länken består av två poler (Fennoskan 1 och 2) och obalanserad ström mellan de två polerna sänds ut i jord via elektroden. De elektriska potentialmätningarna är korrelerade med strömstyrkan genom HVDC-elektroden. De uppmätta potentialerna normaliserades med strömstyrkan vid elektroden och presenteras som en konturkarta för mätningarna på markytan och som grafer för borrhålsmätningar. Resultaten från potentialmätningarna är kompatibla med en konceptuell modell. Ström som sänds ned i marken vid Fågelsundet höjer den elektriska potentialen vid Forsmark och ström flyter då genom jordningarna till ställverkets transformatorer. Strömmen förs sedan vidare från Forsmark via kraftledningarnas fasledningar. Ström kan också föras bort via ledningarnas toppledare och via den nedgrävda jordningskabel som följer stora delar av kraftledningarnas sträckning. Ställverkets jordningsnät kommer alltså att plocka upp ström ur marken när ström skickas ned i marken vid HVSC-elektroden och vice versa. Detta ger upphov till ett lokalt potentialfält runt ställverket med relativ kraftiga gradienter.

Alla resistivitetsmätningar slogs ihop till en gemensam datamängd. Invers modellering utfördes där en blockmodell uppskattades som kan förklara alla mätresultat inom angivna felmarginaler. Blockmodellen ger representativa resistivitetsuppskattningar i en längdskala som är representativ vid till exempel modellering av korrosionshastighet i det planerade djupförvaret. Resistiviteten uppskattades till ungefär 5 000 Ωm mellan KFM07A och KFM24.

Contents

1 Introduction

Earth currents have created problems with corrosion on monitoring equipment in deep boreholes at Forsmark. The major underlying source to earth currents has been shown to be the return current electrode of the Fennoscan HVDC link (e.g. Pedersen et al. 2013). The electrode is located at Fågelsundet, about 25 km north of Forsmark. The possibility for future corrosion due to earth currents at SFR has been treated with numerical modelling by Löfgren and Sidborn (2018) and of copper canisters in a deep repository by Taxén et al. (2014). The modelling requires input parameters both for the electrical potential gradients and for the electric resistivity of the surrounding rock volume. Those two parameters will together give an estimate of the current density in the ground and the direction of current flow.

Measurements of potential gradients caused by earth currents have been carried out in several projects at Forsmark (e.g. Sandberg et al. 2009, Pedersen et al. 2008, 2013). A compilation of different investigations can be found in Thunehed (2017). However, the existing data have only been acquired along single profiles (Sandberg et al 2009) or between pairs of boreholes (Pedersen et al. 2008, 2013). No existing investigation has an aerial coverage. Also, there is a lack of information about vertical potential gradients.

Electric resistivity logging was a standard method for boreholes during the site investigation at Forsmark (e.g. Nielsen et al. 2005). Borehole logging gives information about the electrical properties of the subsurface on a detailed local scale, although the measured apparent resistivity can be significantly biased by the effect of the borehole fluid and the finite dimensions of the borehole probe (Thunehed and Olsson 2004). Estimates of corrosion rates by numerical modelling require knowledge about the resistivity on a length scale that is similar to the modelling experiment, i.e. about a few hundred metres. The resistivity at such a scale is referred to as the bulk resistivity in this report

The bulk resistivity is a combined effect of the porosity, pore space geometry, porewater salinity, fracture frequency, fracture aperture and connectivity between fractures. It is not trivial to estimate the bulk resistivity from the detailed borehole logging data that are available from Forsmark.

There are some resistivity measurements available from the Forsmark area that give information about the bulk resistivity. However, some of those investigations mainly give information about near surface rock volumes down to around 200 m depth (Thunehed and Pitkänen 2003). Deep probing investigations are difficult to carry out close to the power plants or power lines and such measurements have therefore only been carried out at locations away from the planned final repository (Thunehed and Pitkänen 2007). There is thus a lack of information about the bulk resistivity at depths of a few hundred metres, or more, in the Forsmark area.

The purpose of this project is twofold. Firstly, the electric potential field around Forsmark due to earth currents will be mapped and the potential towards depth will be measured in two deep boreholes. Secondly, the bulk electric resistivity will be estimated by making measurements between deep boreholes and between boreholes and the surface.

2 Field survey

A field survey was carried out at Forsmark 16 to 24 October 2017 by staff from GeoVista AB. The monitoring equipment had been temporarily removed from KFM07A and that borehole was therefore available for measurements. KFM24 and the shallower HFM22 were also available (Figure 2-1). Active corrosion protection equipment was disconnected during the survey.

Information about the magnitude and polarity of injected current at the Fågelsundet electrode is necessary for the treatment of survey data. That information was made available from Svenska Kraftnät through SKB. It was not possible for the field crew to know the magnitude or the polarity of the electrode current during measurements and plan the measurements in such a way that all readings were made under similar conditions.

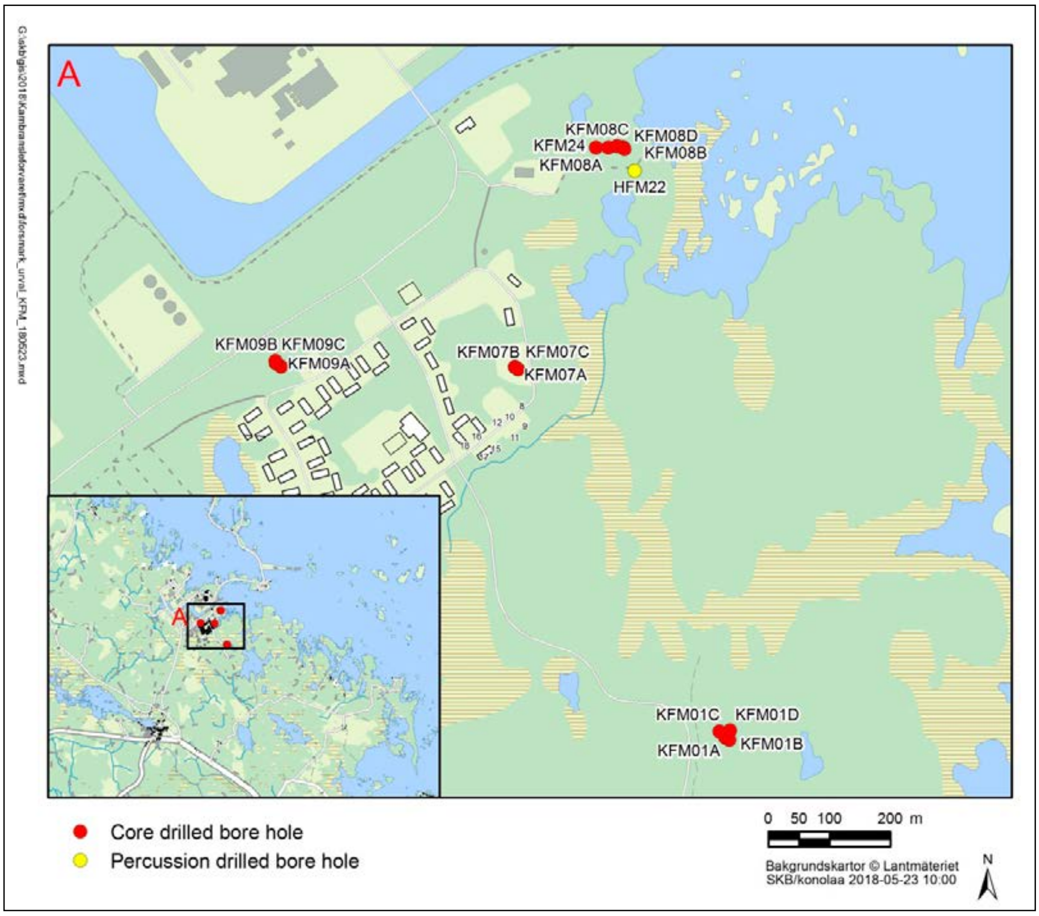

Figure 2-1. *Map showing the locations of boreholes used for the presented measurements. KFM07A, KFM24 and HFM22 were used for resistivity measurements. The electric potential caused by earth currents was measured in KFM07A and KFM24.*

3 Electric potential measurements

Earth currents will create an electric potential field. Potential differences can be measured with a high-impedance voltmeter and non-polarizing electrodes.

3.1 Equipment

Potential measurements were made with an ABEM Terrameter 300C instrument. Stelth 1 Ag-AgCl electrodes from Borin Manufacturing were used for surface measurements, both as reference electrode and for profile measurements. A Stelth 9 Ag-AgCl-electrode was used for borehole measurements. The Stelth electrodes are very stable and the Stelth 9 model is suitable for measurements under high pressure and in high salinity environments, as it originally developed for deep sea applications.

3.2 Survey setup

A reference electrode was placed at Rödgötören, north of Bolundsfjärden (Figure 3-1). All measurements are relative that electrode. Measurements were then carried out along profiles in the investigation area (Figure 3-1). The investigation area is located above a part of the planned deep repository at Forsmark. The time was noted for each reading so that the data later could be normalized to the output current at the Fågelsundet electrode. A test station near drill site 7 was measured at least two times per day. Measurements were also carried out in boreholes KFM07A and KFM24 by lowering an electrode down the holes.

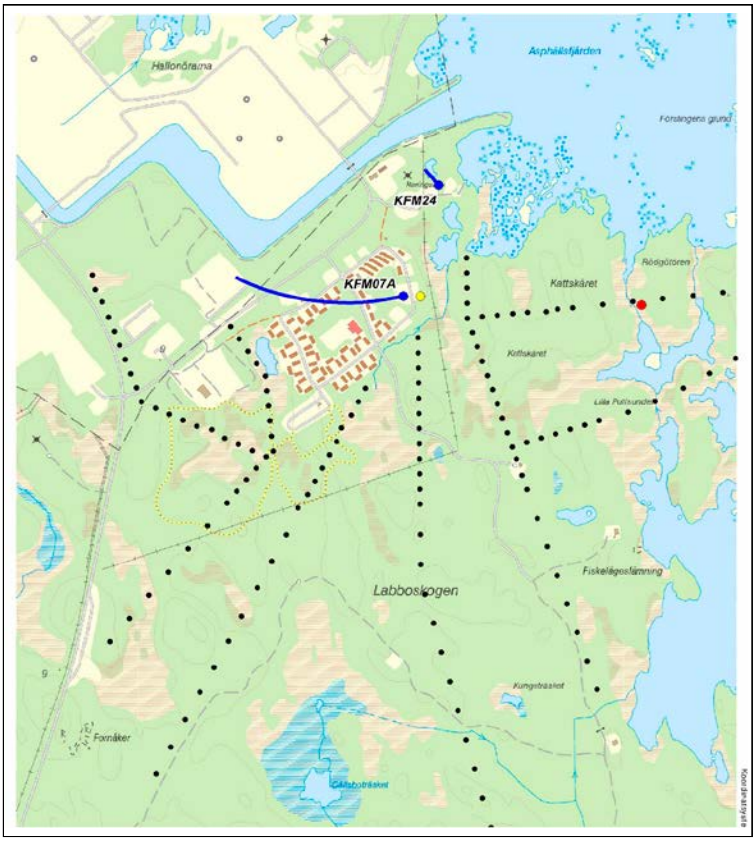

Figure 3-1. *Map showing reference electrode position (red symbol) and the test station (yellow symbol) for potential measurements. Measurements were also carried out along surface profiles (black symbols) and down the boreholes KFM07A and KFM24. The power plant is in the northern part of the map and the AC substation is in the north-western part.*

3.3 Results

3.3.1 Test station

The measurements at the test station are plotted as a function of output current in Figure 3-2. There is a strong correlation between the readings and the electrode current. The red line in the graph represents a linear regression approximation of the relationship. According to this, the potential difference varies with −1.38 mV/A between the test station and the reference electrode. The distance between the stations is 730 m and potential difference between the two stations can thus be estimated to −1.89 V/kA/km. It should also be noted that the regression line in Figure 3-2 does not pass through the origin. Instead the intercept is at −273 mV. The reason for this offset remains to be explained. It is not likely that natural spontaneous potentials would be of such magnitude at Forsmark (Thunehed 2017). It is possible that the potential difference that does not correlate with the electrode current is not constant with time.

3.3.2 Profile measurements

The recorded potential differences along the surface profiles were normalized with respect to the electrode current, taking polarity into consideration. The electrode was used as cathode most of the time during the survey, i.e. with negative polarity (Figure 3-3). However, the westernmost profiles were measured when the electrode was used as anode. A few stations in the north were measured when the current through the electrode was rather weak.

The normalized potential data are illustrated as a contour map in Figure 3-4. A minimum is seen in the north-western part of the map. This is near the AC substation with grounded transformers. It should be noted that the results to some extent can be affected by potentials that are not correlated with the electrode current (cf. Figure 3-2).

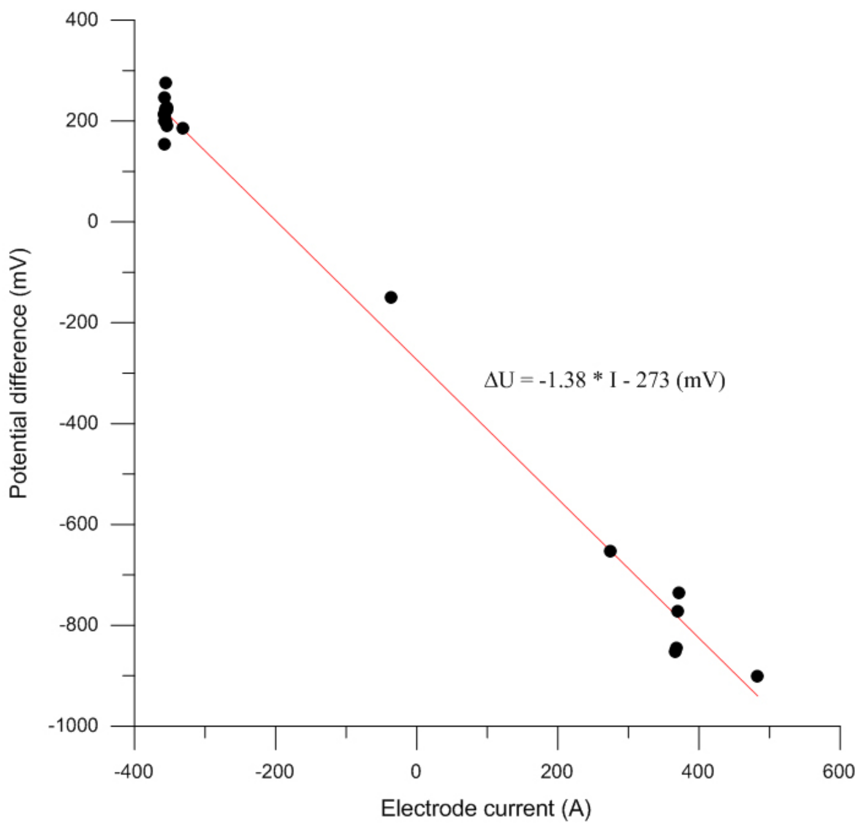

Figure 3-2. *Graph showing the recorded potential difference between the test station and the reference electrode as a function of electrode current at Fågelsundet.*

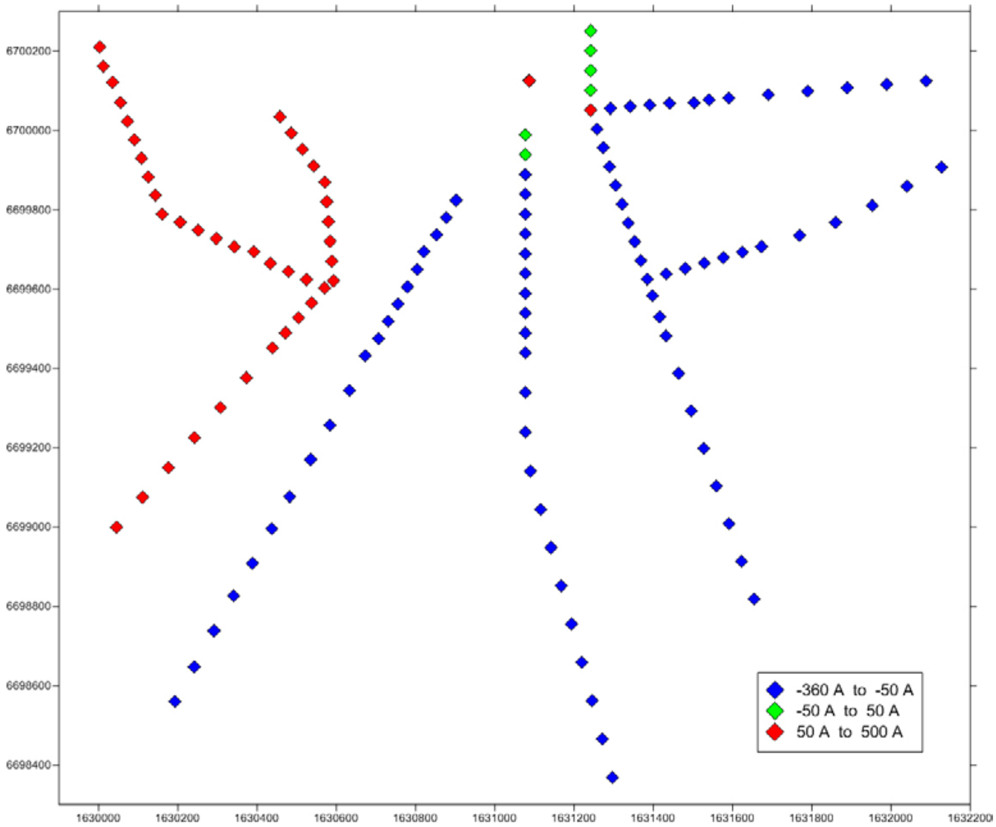

***Figure 3-3.** Map showing electrode current polarity during measurements at surface profile stations. Red symbols show stations that were measured when the electrode current was positive and larger than 50 A. Blue symbols show stations that were measured when the electrode current was negative and larger in magnitude than 50 A. Green symbols show stations that were measured when the electrode current was weak (< ± 50 A).*

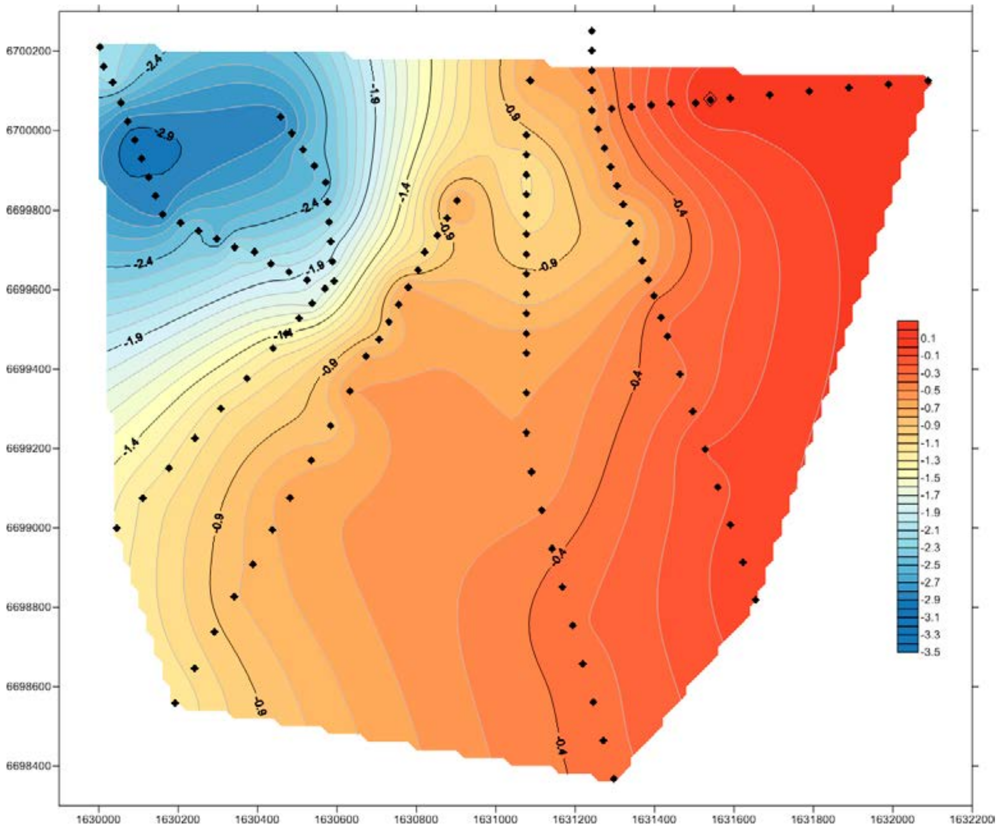

***Figure 3-4.** Contour map illustrating the measured potential differences normalized to electrode current (V/kA).*

3.3.3 Borehole measurements

The recorded potential differences along KFM07A and KFM24 were normalized with respect to the electrode current, taking polarity into consideration. The electrode was used as cathode during measurements in KFM07A (Figure 3-5). The part of KFM07A with casing (0 to 100 m) has positive normalized potentials, whereas negative values are seen for larger depths. The normalized potential just below the casing is around −0.6 V/kA which is consistent with the surface measurements (Figure 3-4). There is a weak positive trend for the normalized potential towards depth. The borehole is directed towards west underneath the potential minimum seen in Figure 3-4. It is possible that the potential gradient would have been greater towards depth for e.g. a vertical borehole at the same position.

The normalized potential in KFM24 is around −0.55 V/kA for the uppermost 90 m (Figure 3-6). The electrode current at Fågelsundet was reduced to low values when the measurements in KFM24 continued to deeper levels. The normalized potential shown in Figure 3-6 therefore gets values that are not related to the use of the electrode below 90 m depth.

The recorded potential difference is around −50 mV below 90 m in KFM24 and increases to around 30 mV towards the end of the hole. Such potential values are not likely to have anything to do with the weak electrode current at Fågelsundet.

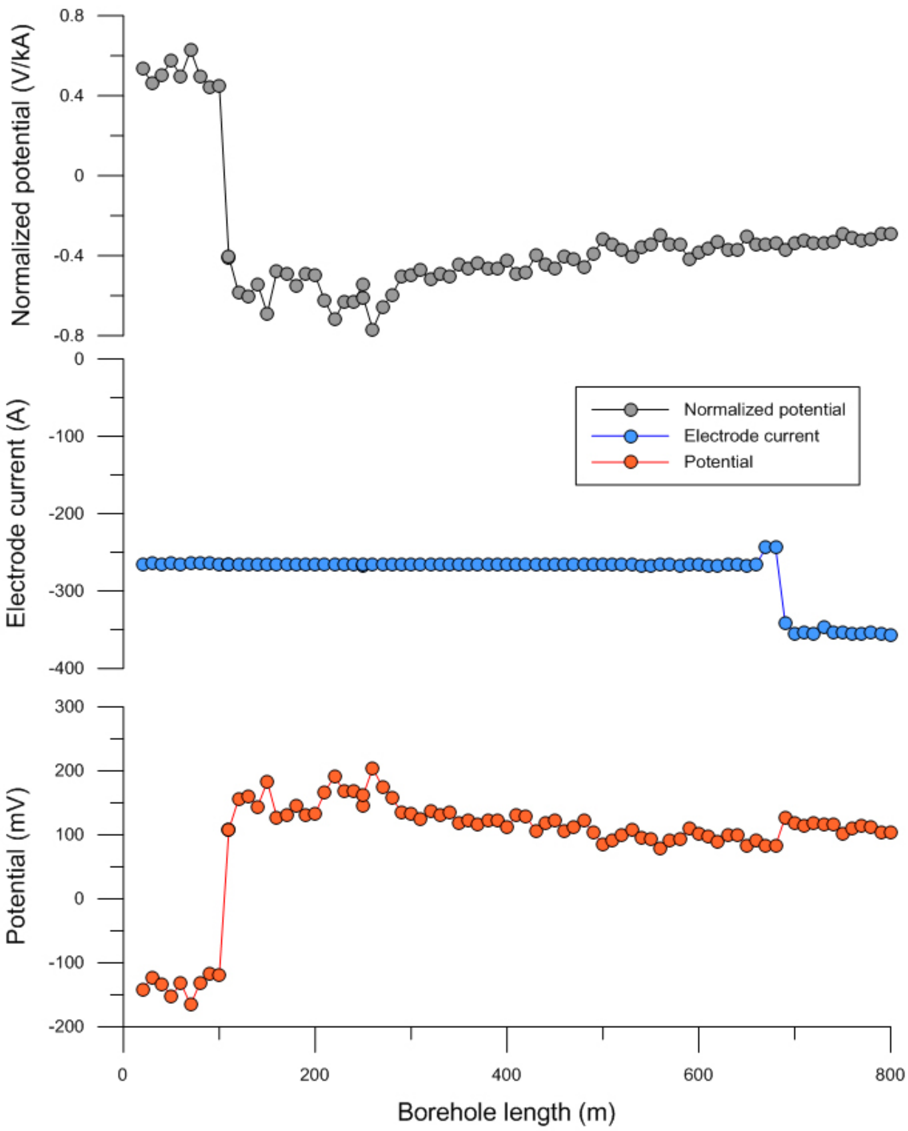

Figure 3-5. *Results from potential measurements in KFM07A. Bottom (red symbols): Recorded potential difference relative reference electrode (mV). Middle (blue symbols): Electrode current during measurement (A). Top (grey symbols): Normalized potential (V/kA).*

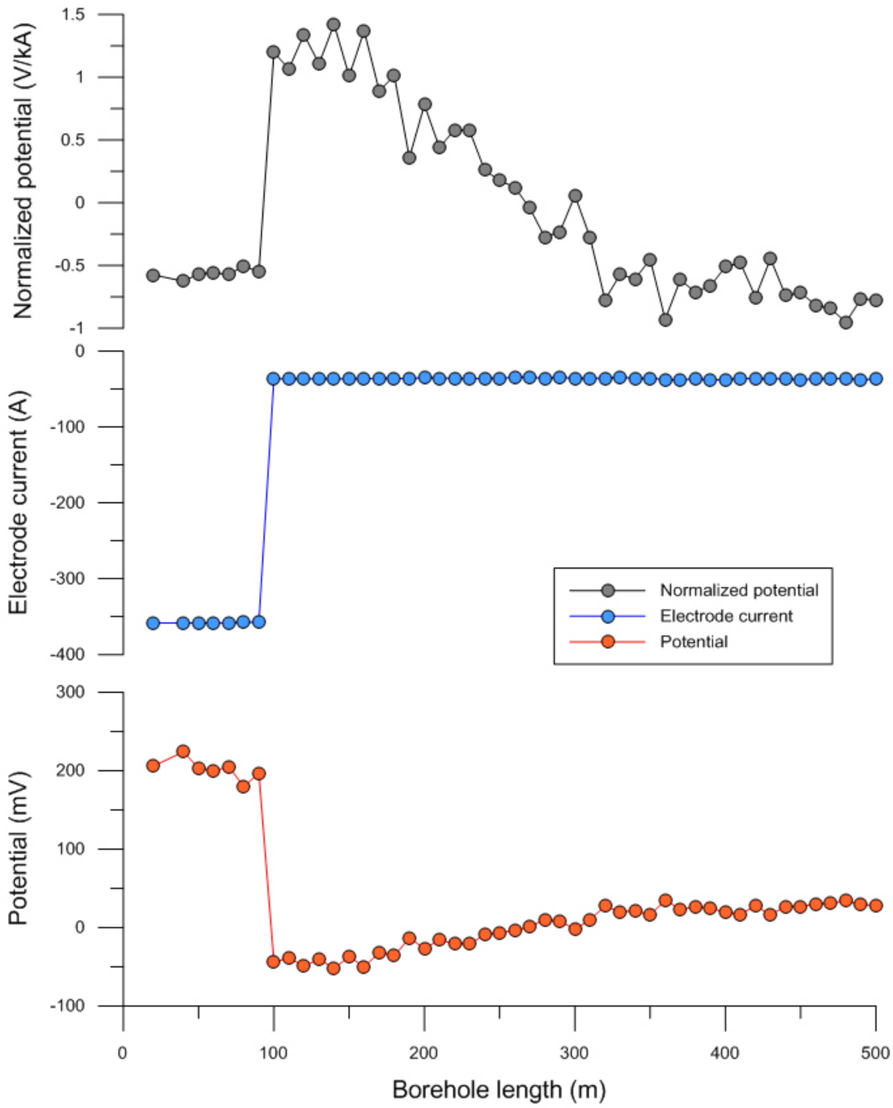

Figure 3-6. *Results from potential measurements in KFM24. Bottom (red symbols): Recorded potential difference relative reference electrode (mV). Middle (blue symbols): Electrode current during measurement (A). Top (grey symbols): Normalized potential (V/kA).*

3.4 Discussions

The potential measurements carried out in this project show results that are consistent with the conceptual model presented in Thunehed (2017). Current of positive polarity through the electrode at Fågelsundet will lift the electric potential at Forsmark, but gradients will be moderate due to the distance to the electrode. However, the transformers of the AC substation at Forsmark have grounded neutrals. Current can be picked up through the transformer neutrals due to the raised potential and the current will be transported away to remote locations via the phase conductors of the AC power lines. Also, there is both a grounded top conductor on the power line towers and a grounded earth cable that follows most of the power line paths. These conductors can also transport current away from the Forsmark power plant area. The grounding net at the AC substation, and possibly other groundings at the power plant, will thus act as a secondary cathode when the Fågelsundet electrode is used as an anode and vice versa. This will create rather strong electric potential gradients around the power plant.

4 Electric resistivity measurements

The electric resistivity of the subsurface can be measured either by inductive or direct current methods. Inductive methods have the advantage of not requiring physical contact with the ground. The investigation depth is determined by the used frequency and very large instrument setups can thus be avoided. However, inductive methods are susceptible to noise generated by e.g. power lines and by long metallic objects, both grounded and not grounded. Deep probing inductive measurements have been carried out in the Forsmark area (Thunehed and Pitkänen 2007), but not around the planned deep repository.

Galvanic measurements are robust and they are usually not seriously affected by power-line noise. However, they can be affected by long grounded metallic objects like e.g. railways or grounded electric power installations. Galvanic measurements were chosen for their robustness and versatility for this project.

Current is injected into the ground with two current electrodes in galvanic measurements. The resulting electric potential is measured between two potential electrodes. The magnitude of the potential difference is dependent upon the electric resistivity distribution in the subsurface around the electrodes. Both current and potential electrodes may be placed either on the surface or in boreholes or as any combination of surface and borehole positions. One single measurement will not yield enough information for a good resistivity estimate. A large number of measurements with different electrode positions are required to sort out the influence from heterogeneities in the ground.

The investigation depth for galvanic measurements is a function of the electrode separation. To estimate the resistivity at the planned repository depth with surface measurements, electrode separations of around two km would be required. Such measurements would be difficult to carry out. The resolution towards depth would also be quite poor. Deep boreholes were therefore utilized in this project.

4.1 Equipment

Current was injected into the ground with a GDD TxII 3600W transmitter. The transmitter was set to transmit a low frequency AC current with a period time of eight seconds. Inductive effects can be safely neglected in a hard-rock environment for such a low frequency and the measurements can be modelled and interpreted as carried out with direct current. An Iris Instruments Elrec Pro receiver was used to measure potential differences. The receiver can measure the potential difference between up to ten electrode pairs simultaneously. The low-frequency signal from the transmitter is identified by the receiver and DC potentials from other sources are automatically compensated for.

Stainless steel rods were used as electrodes on ground surface. A steel rod was also used as a current electrode in KFM07A. Potential measurements were carried out in boreholes with GeoVista inhouse electrode cables. Eight electrodes separated by 10 m are positioned at the end of around 500 m long cables. Three such cables were available and simultaneous measurements in different boreholes were therefore possible.

4.2 Survey setup

The deep boreholes around Forsmark are usually used for monitoring measurements. They are therefore not available for other types of measurements. The monitoring equipment in the borehole KFM07A had been temporarily removed at the time of this survey and KFM07A could therefore be used. KFM24 was also available for measurements. It would have been advantageous to use more than two deep boreholes, but that was not practically possible. Measurements were also made in the shallower, percussion drilled borehole HFM22. Potential electrodes were also placed on the surface along two profiles. The location of the surface electrodes and the projection of the borehole traces can be seen in Figure 4-1. Electrode p07 (Figure 4-1) was connected to the receiver during all measurements and all potential data can therefore use this position as a reference.

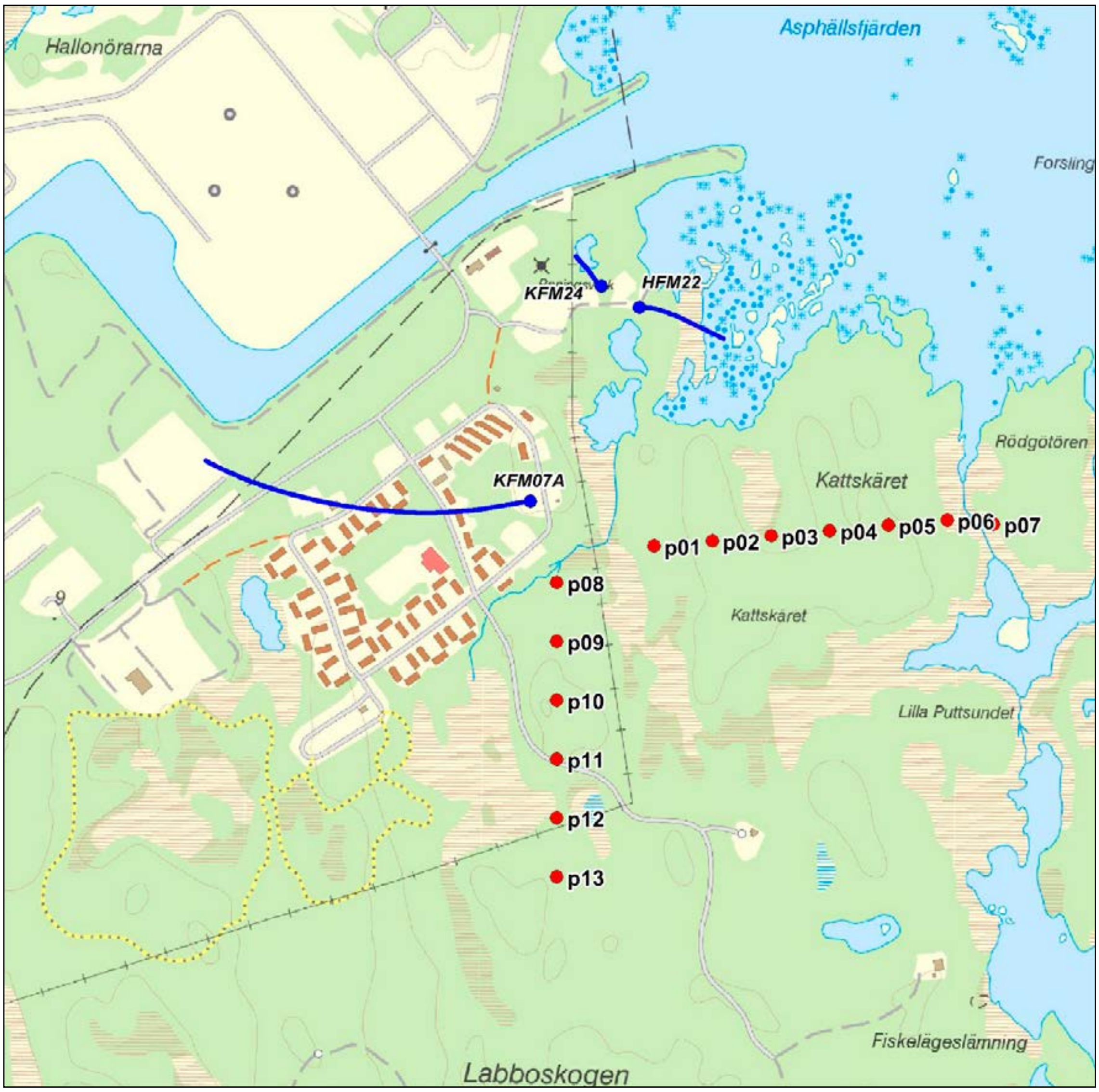

Figure 4-1. Map showing the horizontal projections of the used boreholes KFM07A, KFM24 and HFM22. Surface potential electrodes (p01 to p13) are shown with red symbols.

The measurements were carried out in two steps:

1. A current electrode was lowered into KFM07A (Figure 4-2). The return current electrode was placed close to the small lake Stocksjön, about 2.7 km SSE from KFM07A. Potential electrode cables were placed in KFM24 and HFM22. Measurements started with the current electrode at 170 m borehole length in KFM07A, where borehole casing was assumed to not affect the measurements. The electrode was then moved down the hole in 30 m steps. Readings were made in KFM24 and HFM22 for each current electrode position in KFM07A. The potential electrodes in KFM24 were moved up and down the hole so that measurements were made with the electrode array (eight electrodes with 10 m spacing) at roughly the same vertical depth as the current electrode in KFM07A as well as at more shallow positions. Potential measurements were made between neighbouring potential electrodes and relative the surface electrode p07. The electrode array in HFM22 remained at the same position with electrodes between borehole depths 130 and 200 m. A sketch of the measurement layout is shown in Figure 4-2. The deepest current electrode position in KFM07A was at 800 m borehole length.

2. The current electrode was once again lowered into KFM07A (Figure 4-3). The return current electrode was at the same position as described above. Once again, the measurements started with the current electrode at 170 m borehole length. The electrode was moved in 30 m steps and for each position the potential was measured along the surface profiles (Figure 4-1). A potential electrode cable was lowered into KFM07A, with the deepest potential electrode 300 m above the current electrode. Measurements with such a setup started when the current electrode was at 530 m depth, i.e. the potential electrode array covered the borehole section 160 to 230 m. Both the current electrode and the potential electrode array were then moved in 30 m steps so that the separation between the electrodes remained the same. A sketch of the measurement layout is shown in Figure 4-3. The deepest current electrode position in KFM07A was at 800 m borehole length, corresponding to a depth below surface of 670 m.

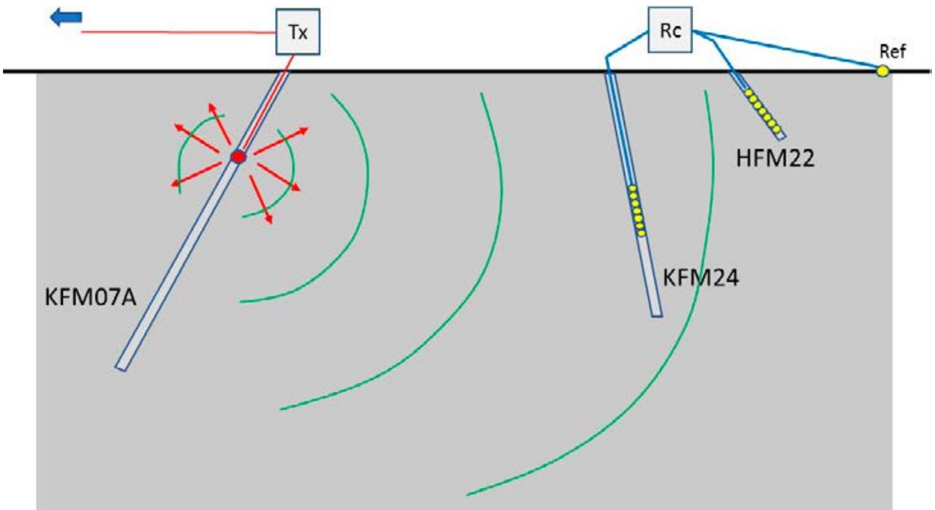

Figure 4-2. *Sketch showing the setup for the first part of the resistivity measurements (not at scale). A current electrode was lowered into KFM07A (red), injecting current into the ground (red arrows). The return current electrode was located about 2.7 km from the boreholes. The green lines represent potential contours. Receiver electrode arrays were lowered into KFM24 and HFM22 (yellow symbols). The electric potential was measured relative an electrode on the surface (p07, Figure 4-1). 22 different current electrode positions were used in KFM07A and three different array positions were used in KFM24.*

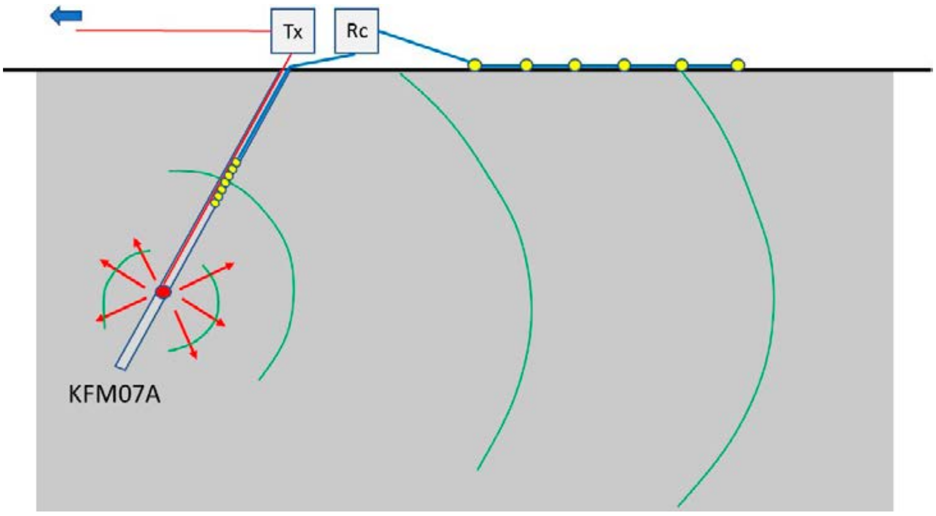

Figure 4-3. *Sketch showing the setup for the second part of the resistivity measurements (not at scale). A current electrode was lowered into KFM07A (red), injecting current into the ground (red arrows). The return current electrode was located about 2.7 km from the boreholes. The green lines represent potential contours. A receiver electrode arrays was also lowered into KFM07A (yellow symbols). The receiver array was kept at a constant separation from the current electrode of 300 m. The electric potential was also measured along two surface profiles. All measurements could be referred to electrode p07 (Figure 4-1).*

4.3 Data processing

The processing of resistivity data included the following steps.

- All data were merged to a common dataset.
- The polarity of the readings was checked. One selectable receiver channel is used for synchronization. That channel will by default get positive polarity in the raw data file. The polarity of all simultaneous measurements is then either correct or reversed, depending on the true polarity of the synchronization channel. The polarity can be checked since the potential should be lowest at the most remote electrode (p07 or p13).
- The receiver measures the potential difference between two neighbouring electrodes in the setup (e.g. between p8–p9, p9–10, p10–p11 etc. in Figure 3-1). The potential relative the most remote electrode is calculated by cumulative addition of recorded signals.
- The measured potential differences were normalized to the magnitude of the injected current.
- Data duplicates were removed. Most setups were measured two or three times to check repeatability. The reading with the lowest recorded standard deviation was kept.
- Coordinates (east, north, elevation) were assigned to all electrode positions. Borehole survey data from SKB were used.

When the data were studied it became evident that some surface electrodes were affected by disturbances since they consistently gave unreasonable results. Incorrect data may result in strongly biased results in the inversion (Section 4.3.1). All data measured with electrodes that were suspected to have been disturbed (p03, p04 and p05, Figure 4-1) were therefore removed from the dataset before inversion. It was also suspected that two electrode pairs in one of the receiver borehole cables were poorly insulated from each other. Measurements with those electrodes were also removed from the dataset before inversion.

4.3.1 Inversion

Inversion is a process where the parameters of a model are iteratively adjusted until the calculated response of the model to the measurement setup explains the data within specified data errors. The inversion program DCIP3D from University of British Columbia (Li and Oldenburg 2000) was used in this project. The model consists of a mesh with rectangular blocks, where the electric conductivity of each block can be varied. The size of the blocks was 10 m in the horizontal directions and 8 m vertically around electrode positions. Padding blocks with gradually increasing size outwards and towards depth were added so that the total size of the model was 4 944 by 6 565 by 3 991 metres (east, north and vertical directions respectively). The size of the model was large enough to include the return current electrode. The total number of blocks in the model was 398 848.

The number of unknowns in the inverse problem equals the number of blocks in the model. This number is far greater than the number of measurements. The property of many blocks is also not constrained by the data. Additional constraints must therefore be applied on the model for the process to converge. Basically, a model is sought that satisfies three criteria.

1. The calculated electric potential field should fit the measurements within specified data errors.
2. The sum of all anomalous electric conductivity values for model blocks should be minimized.
3. The sum of all electric conductivity gradients at block boundaries should be minimized in the east, north and vertical directions.

Criteria 2 and 3 are balanced against each other by specifying the magnitude of so called smoothing filters. Also, a reference is subtracted before applying criteria 2 and 3 above. The default reference is a constant conductivity value that can be seen as a background conductivity level. From this follows that the default reference for gradients is zero. However, it is possible to define other reference models. In such a case the algorithm will try to find a model with a good fit to the data, that at the same time resembles the reference model.

Model blocks that are not constrained by the data will be assigned conductivity values that are close to the reference value.

The user must specify different parameters as input to the inversion program. Default values were given for most parameters with the following exceptions.

- Data errors were specified as 3 % plus 0.15 mV/A. Larger errors (up to 15 %) were assigned to some measurements that were regarded as possibly being disturbed or noisy.
- Different reference conductivity values were tested in the inversion, ranging from 0.04 to 0.5 mS/m (corresponding to 2 000 to 25 000 Ωm resistivity). Suitable reference values were selected after comparisons between the data and homogeneous half-space models. A reference model with gradually increasing conductivity with depth was also tested.
- Different values for smoothing filters were tested.

The inversion results were fairly consistent in parts of the model that were well constrained by the data, regardless of parameter settings. The results that are shown below are for a reference value of 0.1 mS/m (corresponding to 10 000 Ωm resistivity) and smoothing filters of 300 m horizontally and 75 m vertically, i.e. stronger smoothing in the horizontal directions.

4.4 Results

The conductivities of most blocks in the inversion model are not well constrained by the data since the coverage of electrodes was coarse in the field survey. Primarily, the volume between electrode positions in KFM07A and KFM24 was investigated. Conductivity values were therefore extracted from the model along three profiles.

- Positions along KFM07A shifted 100 m towards KFM24.
- Positions along KFM24 shifted 100 m towards KFM07A.
- Positions at positions half-way between KFM07A and KFM24.

The reason for not extracting values from the actual electrode positions is that the inversion algorithm tends to assign anomalous values to model blocks close to electrodes to fit the model to e.g. noisy readings.

The extracted model values are presented as estimated resistivity versus depth below ground surface in Figures 4-4 to 4-6. Only values down to 500 m below ground surface are shown, since the model is poorly constrained by the data at larger depths.

Figure 4-7 illustrates the fit between the model response and the measured data. The fit is acceptable except for a few measurements. Poor fit can be due to a number of reasons.

- Measurements can be affected by noise, inaccurate calibration, infrastructure or other disturbances.
- The discretization of the model into blocks may not be fine enough everywhere.
- Resistivity anisotropy is not accounted for during the inversion since that would introduce too many degrees of freedom in the model. Rocks at Forsmark are often foliated and resistivity anisotropy can be significant (Thunehed and Pitkänen 2003).
- The inversion is an iterative process that is strongly non-linear. The algorithm can therefore get stuck at a solution that is not corresponding to the best possible fit to the data.

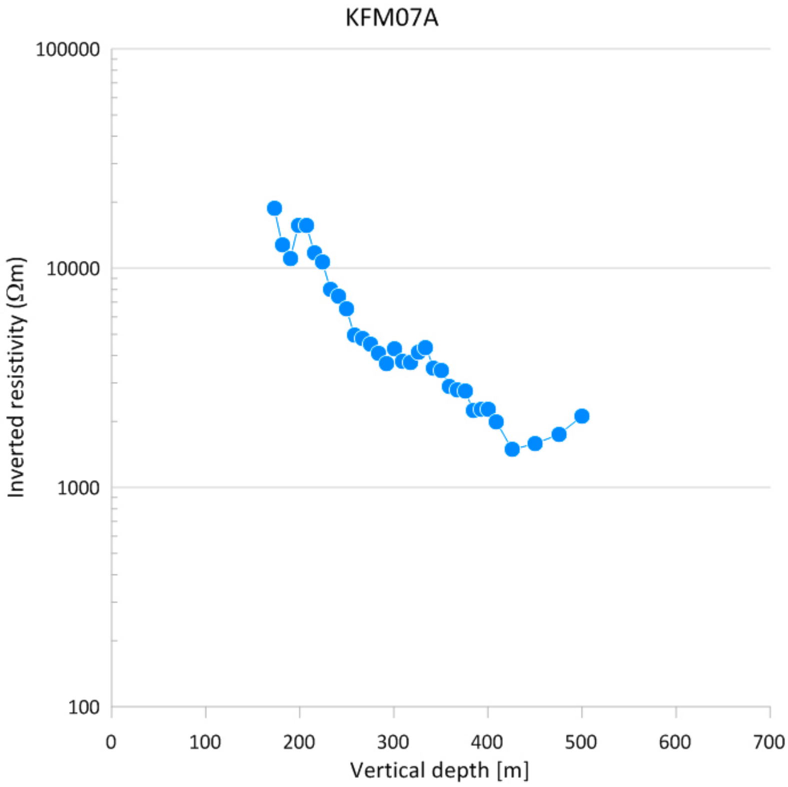

Figure 4-4. *Resistivity values extracted from inversion model. The values are extracted from positions 100 m from KFM07A in a direction towards KFM24.*

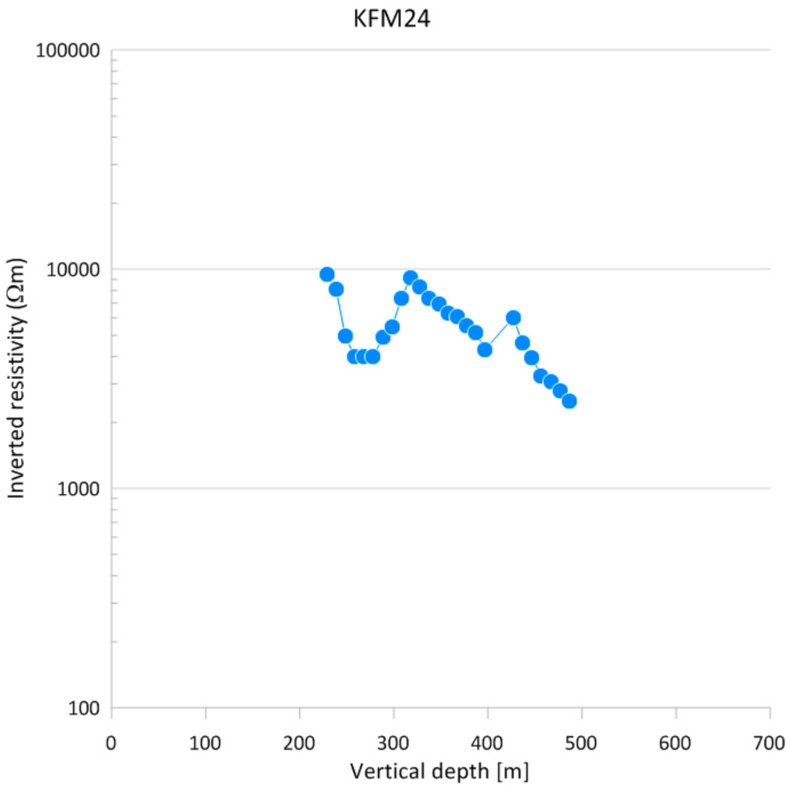

Figure 4-5. *Resistivity values extracted from inversion model. The values are extracted from positions 100 m from KFM24 in a direction towards KFM07A.*

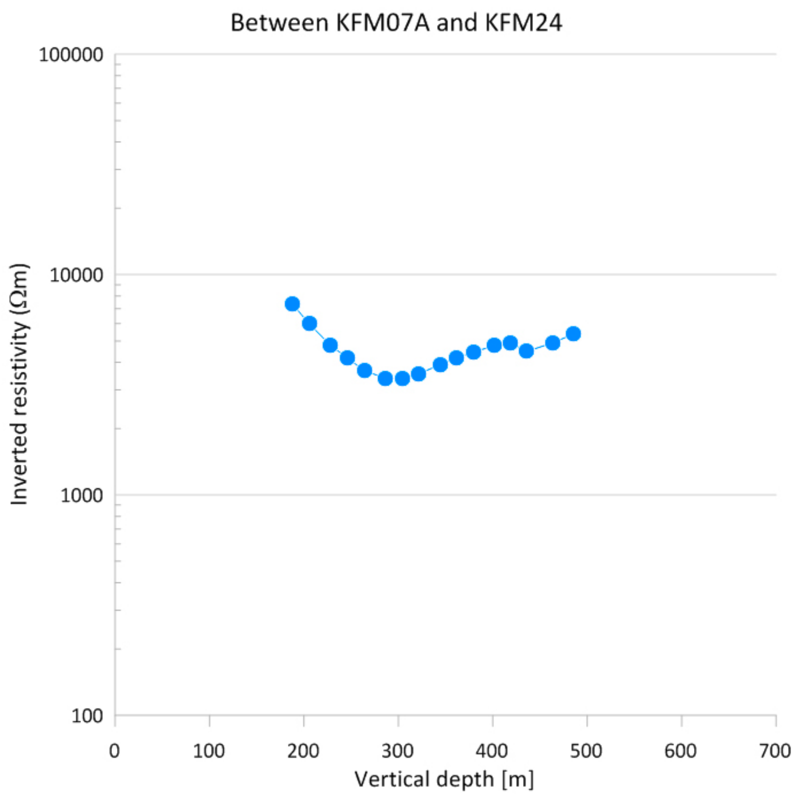

Figure 4-6. *Resistivity values extracted from inversion model. The values are extracted from positions half-way between KFM07A and KFM24.*

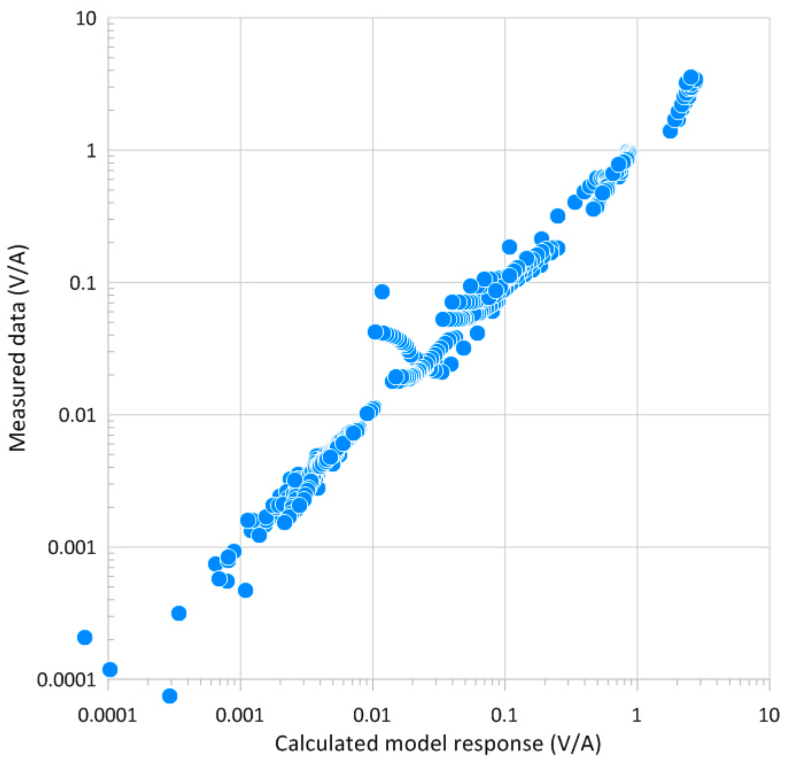

Figure 4-7. *Cross-plot between the calculated model response for the inversion model and the measured data.*

4.5 Discussions

The distance between electrode positions in KFM07A and KFM24 is around 500 m, i.e. about the same distance as the vertical depth to the deepest electrode positions. It is therefore not expected that the used electrode setup will resolve resistivity heterogeneities in the subsurface well. Such an investigation would require the use of deeper boreholes, a larger number of boreholes, shorter separation between the boreholes and a larger number of surface electrodes.

The scope for the resistivity measurements was to estimate the electric resistivity at the depth of the planned repository on a bulk scale, i.e. the effective resistivity of intact rock, pore space, fractures and deformation zones combined on a length scale of a few hundred metres. The estimated resistivity at the depth of the planned repository is roughly in the interval 1 500 to 6 000 Ωm in Figures 4-4 to 4-6. A representative estimate of the bulk resistivity, not very much affected by local heterogeneities, is seen in Figure 4-6 halfway between KFM07A and KFM24. The estimated resistivity at the depth of the planned repository is around 5 000 Ωm in Figure 4-6.

5 Conclusions

Electrical potential gradients are a driving force for corrosion. The potential measurements carried out in this project imply that strong potential gradients are related to the grounding net of the AC sub-station of the Forsmark power plant. The potential is raised (or lowered, depending on polarity) at Forsmark when current is transmitted through the HVDC electrode at Fågelsundet, around 25 km towards north. However, the primary potential gradients due to use of the electrode are weak at Forsmark due to the distance to the electrode. Instead, strong gradients at Forsmark are created by current picked up by the grounding net of the AC sub-station due to the raised (or lowered) potential. The picked-up current is transmitted to remote locations via the AC phase conductors, the top conductors of the line towers and the buried ground cables that follow much of the power line paths. The grounding net will thus act as a secondary current source (or sink). The potential field due to such a source is expected to form semi-spherical shells of constant potential, distorted by resistivity heterogeneities. The potential field will thus have both vertical and horizontal components.

The bulk resistivity of the rock at a few hundred metres depth was estimated by this study to around 5 000 Ωm at Forsmark. This can be regarded as a normal value for hard rock with low fracture frequency and low porosity, saturated by saline to brackish water. The value may be used as a normal value for numerical modelling of corrosion of copper canisters in a future repository. The combination of knowledge of potential gradients and bulk resistivity also provides an estimate of the current density. The potential gradient is around 2 mV/m/kA at the surface around drill site 7. A rough estimate for the current density in normal rock in this area would then be 0.4 $\mu A/m^2$ for an electrode current of 1 000 A at Fågelsundet. However, the current density will vary considerably locally due to resistivity heterogeneities.

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