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Theoretical modelling based on physical properties of underground constructions at Forsmark

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

Data in SKB's database can be changed for different reasons. Minor changes in SKB's database will not necessarily result in a revised report. Data revisions may also be presented as supplements, available at www.skb.se.

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Abstract

The Swedish Nuclear Fuel and Waste Management Company (SKB) has the responsibility for the final disposal of radioactive waste from Swedish nuclear power plants and plans to design, construct and operate a final repository for spent nuclear fuel in accordance with the KBS-3 method at Forsmark. In the assessment of long term safety of a final repository future human actions have to be considered. This study has been undertaken to provide input to an assessment of the likelihood that someone in the future during exploration for mineral resources would discover the repository. The construction of a repository will give other geophysical properties to the underground constructions compared to the pre-existing bedrock. Possible geophysical anomalies caused by the repository may be interpreted as interesting targets that could be further investigated by drilling.

In this report the geophysical response of a radioactive waste repository buried at a depth around 500 m below the surface in the bedrock at Forsmark is modelled for several different geophysical methods. These include magnetics, gravity, IP, resistivity, Transient Electromagnetic (TEM) and reflection seismics. The modelling is limited to surface geophysical methods.

A simplified model of the repository was generated based on MicroStation design files that provided information on tunnel and canister-hole geometries such as area and dimensions of the different tunnel types. The ramp, shafts and other basic infrastructure items were not included in the generalised models. The repository was divided into nine fairly homogenous sub-areas. One generalised solid was created for the deposition tunnels and canister holes respectively for each sub-area.

Physical properties of selected materials were used as input parameters in the modelling work. The parameters were determined from literature studies (SKB reports and scientific papers) and from direct measurements on samples.

The gravity response of the repository constitutes a gravity minimum of 0.009 mGal above the centre of the repository. The anomaly level is very small and is comparable to the noise level of modern gravity meters and the repository anomaly is less than 1% of the natural variation in the area.

The magnetometry response from the repository gives a magnetic span from –0.01 to 0.06 nT, in total a range of 0.0675 nT. This is within the noise level of a modern magnetometer and compared to the natural variation of around 1,200 nT at Forsmark the contribution from the repository can be considered as negligible.

For TEM the repository generated a secondary field for the vertical component that is approximately twice as high compared to a model without the repository. However, the natural resistivity variations in the bedrock may be of at least one order of magnitude greater and it is therefore hardly likely that a minor, although measurable, change in apparent resistivity as expected from the repository would be experienced as a possible mineralization at depth.

The modelled responses from the repository for IP and resistivity measurements are significant. However, the anomalies from the repository are very small in amplitude and they do not show a distinct spatial distribution. When relating the responses from the theoretical calculations from the repository with real survey data from Simpevarp, that represents a typical geological situation comparable with the one at Forsmark, it becomes probable that the response from the repository will be obscured by geological noise.

For reflection seismics two models were tested, one without a repository and one with the deposition tunnels of the repository included. There is a clear seismic response from the repository in the synthetic sections. This is due to the large contrast in velocities (both P-wave and S-wave) of the bentonite compared to the surrounding granitic rock used in the modelling and it is likely that the repository would be detected in real data.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) har ansvaret för att planera, bygga och driva ett slutförvar för högaktivt radioaktivt kärnavfall från svenska kärnkraftverk enligt KBS-3-metoden. Förvaret ska ligga i Forsmark. I den säkerhetsbedömning som görs av slutförvaret ingår att ta hänsyn till framtida mänskliga aktiviteter och påverkan. Denna studie har gjorts för att tillhandahålla information för en bedömning huruvida människor i framtiden i sökandet av mineraltillgångar skulle kunna finna förvaret. Ett slutförvar medför en förändring av bergets fysikaliska egenskaper. Denna undersökning syftar till att belysa risken för att någon i framtiden ska tolka möjliga geofysiska anomalier efter mätning på marken som så pass intressanta att man utför vidare undersökningar med borrning.

Den geofysiska modellresponsen från ett slutförvar för använt kärnbränsle på 500 meters djup under marknivån i Forsmark har beräknats för ett antal geofysiska metoder. De metoder som använts är magnetometri, gravimetri (tyngdkraft), inducerad polarisation (IP), elektrisk resistivitet, transient elektromagnetism (TEM) och reflektionsseismik. Modellering är endast utfört för markmätningar (ej borrhål eller från luften).

En förenklad förvarsmodell byggdes utifrån MicroStation designfiler som innehöll information om tunnel- och kanistergeometrier och tvärsnittsarea för olika tunneltyper. Ramp, schakt och annan infrastruktur inkluderades inte i den generaliserade modellen. Förvarsmodellen delades in i nio delområden. En separat generaliserad solid för depositionstunnlar och kanisterhål skapades för varje delområde.

Fysikaliska egenskaper för alla kända signifikant material användes som ingångsparametrar i modelleringsarbetet. Parameterdata bestämdes genom litteraturstudier och mätningar på prover.

Resultaten av våra undersökningar visar att tyngdkraftsresponsen rakt ovanför förvaret är –0,009 mGal. Anomalin är storleksmässigt likvärdig med brusnivån för en modern gravimeter och anomalin utgör mindre än 1 % av de naturliga variationer i tyngdkraftsfältet som förekommer i Forsmark.

Den modellerade magnetiska responsen varierar mellan –0,01 nT och 0,06 nT. Amplituden är likvärdig med brusnivån för en modern magnetometer och i förhållande till de naturliga variationerna i jordmagnetiska fältet i Forsmark på cirka 1,200 nT så är bidraget från ett slutförvar försumbart.

För TEM-modellen genererar förvaret ett sekundärfält vars vertikala komponent är dubbelt så kraftig som för modellen utan förvar. Detta bygger dock på en konstant resistivitet i den omgivande berggrunden. I en verklig geologisk miljö är det rimligt att berggrundens resistivitet varierar med cirka en tiopotens, vilket då medför att den anomali förvaret orsakar, trots att den är mätbar, knappast skulle tolkas som en möjlig mineralisering på djupet.

Modellresponsen från ett djupförvar är tydlig både för IP och resistivitet. Anomalierna för respektive metod har dock svag amplitud och uppvisar ingen entydig rumslig fördelning. Jämför man modellresponsen med verkliga data från mätningar i Simpevarpsområdet, som i detta sammanhang är geologisk jämförbart med Forsmark, framstår det mest sannolikt att responsen från förvaret skulle döljas av geologiskt brus.

Den reflektionsseismiska modelleringen utfördes på två modeller, en med och en utan ett förvar. Det finns en tydlig respons från förvarsmodellen i det syntetiska seismogrammet. Detta orsakas av den stora hastighetskontrasten (både P-våg och S-våg) mellan bentonitleran i förvarstunnlarna och omgivande berggrund. Slutsatsen är att ett förvar skulle detekteras i riktiga data vid en framtida mätning med denna metod.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has the responsibility for the final disposal of radioactive waste from Swedish nuclear power plants. Spent nuclear fuel is presently transferred successively from the Swedish nuclear power plants to a central interim storage facility for spent fuel near Oskarshamn (Clab). SKB plans to design, construct and operate a final repository for spent nuclear fuel in accordance with the KBS-3 method at Forsmark. The spent nuclear fuel will be encapsulated in watertight and load-resistant copper canisters. The canisters are deposited in crystalline rock at a depth of about 500 m and surrounded by a buffer of bentonite clay to prevent flow of water and to protect the canisters. Tunnels and rock caverns are to be backfilled with clay when the disposal is completed. This construction of a repository will give other geophysical properties to the underground constructions compared to the pre-existing bedrock.

In the assessment of long term safety of a final repository future human actions have to be considered. This study has been undertaken to provide input to an assessment of the likelihood that someone in the future during exploration for mineral resources would discover the repository. Possible geophysical anomalies caused by the repository may be interpreted as interesting targets that will be further investigated by drilling or other methods.

This aspect of a radioactive waste repository has been studied earlier by /Parasnis 1982/ who concluded that detectable geophysical anomalies may develop due to a repository by measurements at the surface by radar, electric, electromagnetic and geothermal methods. Especially the last mentioned method would probably generate significant anomalies above the centre of the repository, even in shallow drillholes.

1.1 Objective and scope

The aim with this report is to quantify the geophysical response of a radioactive waste repository buried at a depth around 500 m below the surface in the bedrock at Forsmark. Hence, the main question:

Is there a measurable response from the repository, at the ground surface, for a number of geophysical methods including: magnetics, gravity, transient EM (TEM), resistivity, induced polarization (IP) and reflection seismics.

The layout of the radioactive repository at Forsmark is presented by /Hansson et al. 2009/ with complementary information about tunnels etc described by /SKB 2006/. The geometrical complexity of the repository is shown in the proposed layout in Figure 1-1. The capabilities of the software available for modelling of the geophysical methods above vary with respect to the allowed geometrical complexity of the models. While magnetics and gravity may be modelled in 3D with quite high complexity, some other methods have to be modelled with a high degree of generalization; among the latter is found reflection seismics which has been modelled in 2D. Among the limitations introduced in the modelling is also the decision to concentrate only on the tunnel system located at depth, i.e. transport tunnels for communication between the repository tunnels and the surface are omitted in the modelling. Furthermore, the response of buried targets to geophysical methods at the ground surface is higher than in airborne measurements. Hence, there is no need for modelling of geophysical measurements from airborne platforms.

The bedrock of the Forsmark area is well characterized and the input parameters representing rock volumes surrounding the repository are expected to be well enough defined. The material filling the tunnels and the repository holes consists of bentonite. The electrical properties of bentonite is essential for the modelling of the response for IP, resistivity and TEM, P- and S-wave velocities, and density of the clay are important for the reflection seismics. The property of the canisters used is also needed in the modelling, here the electrical conductivity, the magnetic properties and density are needed.

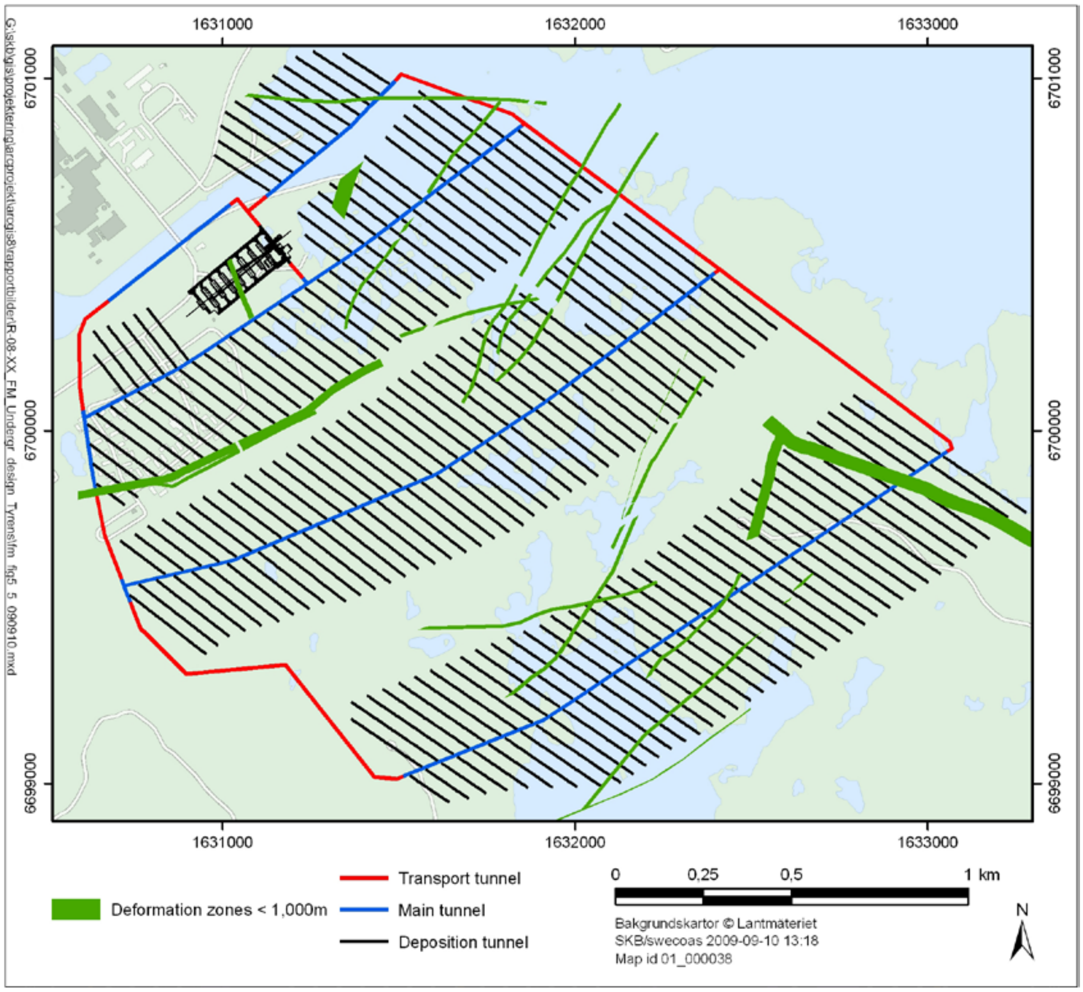

Figure 1-1. *Proposed layout of the repository at the depth of –470 m /from Hansson et al. 2009/.*

In the evaluation of the response it is important to relate it to the geological noise existing in the area. The geological noise consists of all the anomalies induced by existing geological units and features. To the geological noise is added instrumental or internal noise from the measurement equipment. Furthermore, today the noise consists also of external noise from traffic, power transmission etc. In the future such noise may be absent, as today, or worse. For gravity, magnetometry, resistivity and reflection seismics, measurements exist from the area which can be used to estimate part of the noise level. Regarding future geophysical survey systems it is difficult to estimate their character of performance, but probably their internal noise levels will have been radically reduced; however, it is not considered meaningful to introduce a quantification of future performance figures; the discussion on signal/noise ratios will thus primarily be based on the systems which have already been used in the Forsmark area, or systems which are available on the market today. The suggested approach is shown in Figure 1-2.

There will be a number of uncertainties left after the finalization of this task. One of the most important is whether the calculated response is valid considering the simplifications necessary to introduce in the geometrical complexity of many of the models. This uncertainty will be explained in the light of the principles behind each of the geophysical methods and is expected to give a qualitative indication of the level of prognosis regarding the response.

The choice of geophysical methods is debatable. However, by choosing many methods the risk is minimized to overlook a method with a potential to detect the repository.

The geophysical interaction between different features in the bedrock, like deformation zones, and the repository has to be disregarded in the modelling as the complexity rises to levels beyond what is possible to solve at this stage.

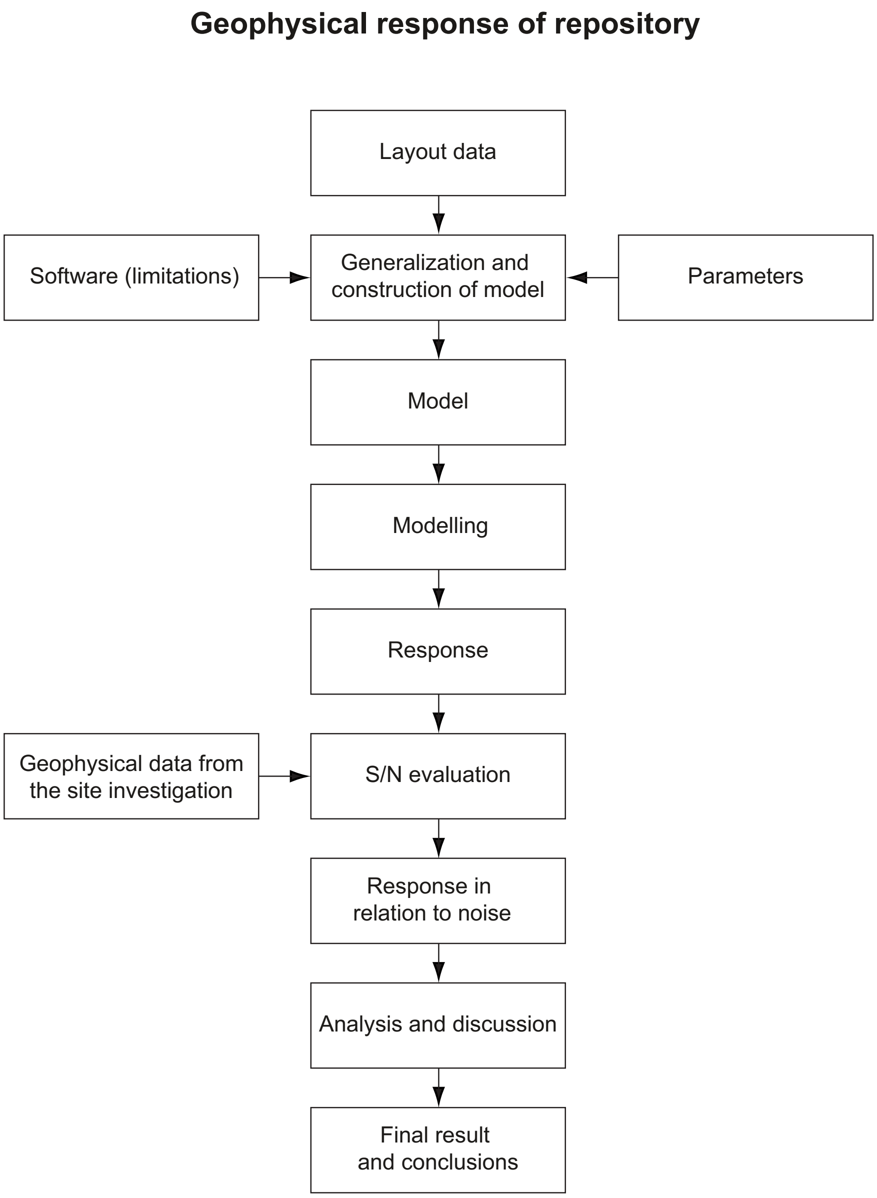

Figure 1-2. *Sketch showing the items involved in the modelling of the "Geophysical response of the repository". This sketch is method specific meaning that each method must go through all steps.*

1.2 Input data

The layout and construction plan of the repository at Forsmark is presented by /Hansson et al. 2009/.

The layout of the repository was delivered in MicroStation design files to SKB by Tyréns in June, 2009. Details of the exact location of canisters, deposition tunnel end-points, break-points in transport tunnels etc were delivered in Excel-files.

Physical properties of selected materials (bentonite clay, canisters etc) and of the host rock were determined by measurements on samples and from literature studies of scientific papers, thesis, SKB reports, internal SKB documents and personal communication with SKB staff.

The parameters to be determined were density, magnetic susceptibility, natural remanent magnetisation, electric resistivity and induced polarisation (IP). The materials are bentonite clay, canisters, reinforcement bars/net, shotcrete (including 3 weight% steel fibres) and the main host rock of the repository, which is meta-granite to granodiorite.

A list of physical properties and data references is presented in Table 3-1, Chapter 3-1.

1.3 Modelling tools – software list

The modelling of gravity and magnetics was primarily based on the use of the ModelVision ver.10, © Encom Technology. For the calculation of the magnetic response from the cast iron in the canisters (approximated to magnetic dipoles) an in-house program code was developed at GeoVista.

The response modelling of TEM used the program Loki which is a part of the P223 suite of EM modelling software from Amira, Australia.

Modelling of Induced Polarization and resistivity utilized the geometrical models from gravity and magnetic studies (located in ModelVision); from those models a voxel model was constructed for use in the programme DCIP3D by UBC, University of British Columbia within which the response was then calculated.

The modelling of the response for reflection seismics utilized an elastic 2D finite difference modelling code that is available in Seismic Unix (www.cwp.mines.edu).

2 Approach

2.1 Import of layout and general simplifications/adjustments

The MicroStation design files contain non-standard (non MicroStation) elements that could not be exported to 3-dimensional DXF or other formats for triangulation, they did, however, provide information on tunnel and canister hole geometries such as area and dimensions of the different tunnel types etc.

The base for constructing the generalised triangulated solids has been the detailed co-ordinate files describing the start and end-points of deposition tunnels, the centre point of the top surface of the canister holes as well as the break points for the two different sizes of transport tunnels.

The ramp, shafts and other basic infrastructure items were not included in the generalised models.

The repository was divided into nine fairly homogenous sub-areas as shown in Figure 2-1 below. One generalised solid each was created for the deposition tunnels and canister holes respectively for each sub-area.

Deposition tunnels

The co-ordinates given for the deposition tunnels correspond to the centre-point for the tunnel floor. The tunnels have a width of 4.20 m and a height of 4.80 m, the tunnel area is 19.06 m^2.

All points for the sub-area were imported into MicroStation, lines were constructed between the points for the outside (SW and NE extremes) tunnels. These lines were moved parallel outwards 2.10 m, corresponding to half the width of the tunnels.

The resulting points and lines were exported to DXF and imported into Surpac for triangulation of the bottom surface of the generalised volume. A copy of this surface was created 4.80 m above the bottom and a solid created between them. The solid was exported to DXF.

A sub-set, consisting of the western parts of sub-area DC-south is shown below, in Figure 2-2, to illustrate the construction of generalised volumes instead of individual tunnels. The 8 deposition tunnels are entirely enclosed in the sub-volume created.

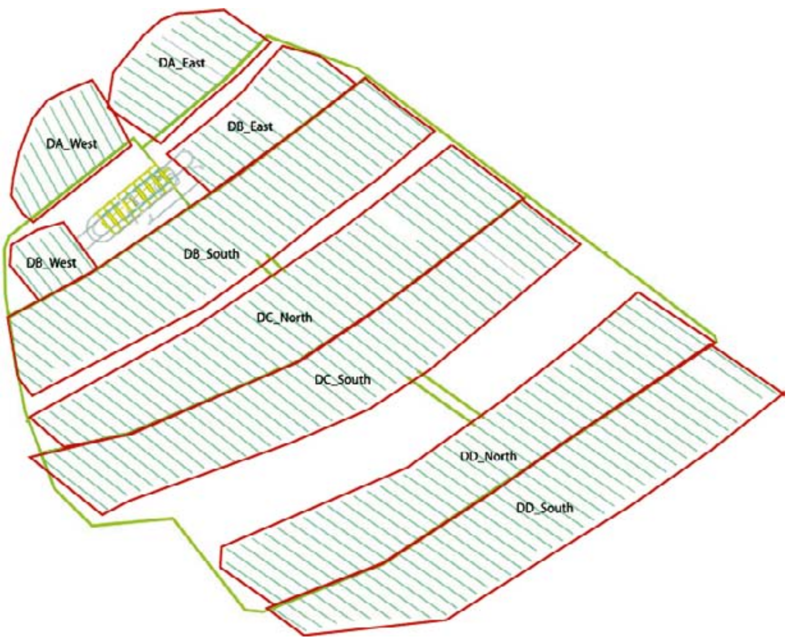

Figure 2-1. *Definition of sub-areas for repository.*

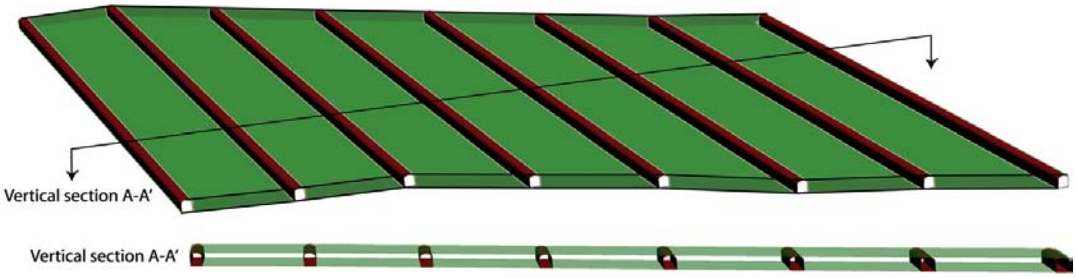

Figure 2-2. *Creation of sub-volumes to replace deposition tunnels.*

Canister holes

The co-ordinates given for the canister holes correspond to the centre-point of the opening of them, the holes are 1.75 m in diameter and 8.00 m deep.

All points for the sub-area were imported into MicroStation, lines were constructed along the four sides of the area and moved in parallel outwards 0.875 m, corresponding to the radius of the hole.

The resulting points and lines were exported to DXF and imported into Surpac for triangulation of the top surface of the generalised volume. A copy of this surface was created 8.00 m below the top and a solid sub-volume created between them. The solid was exported to DXF.

Transport tunnels

There are two types of transport tunnels, having widths of 7.00 m and 10.00 m respectively (Figure 2-3).

Generalised shapes or sections corresponding to each tunnel type were created in Surpac. The points corresponding to each tunnel type and segment were imported into Surpac and the sections were extruded along the segment to create triangulated solids. In all, 13 segments were created for the 7.00 m tunnels and 8 segments for the 10.00 m tunnels. For these elements no sub-volume was created.

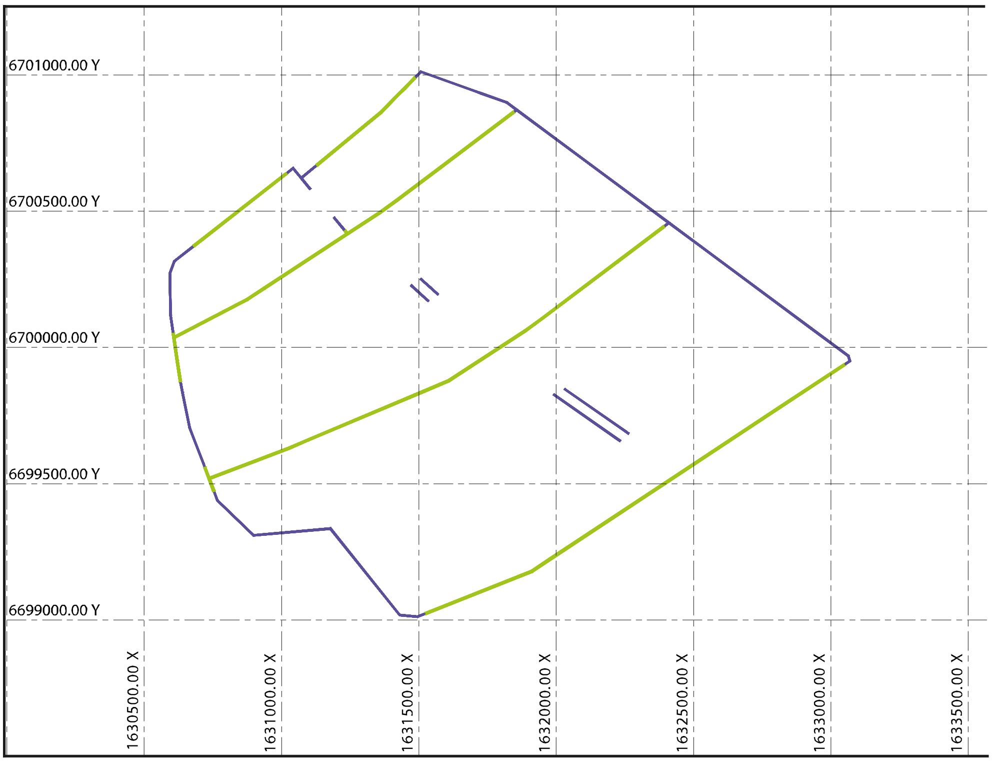

Figure 2-3. *Transport tunnel types. Green=10 m width, violet=7 m width.*

2.2 Modelling strategy – further method-specific simplifications of the input layout – choice of parameters

2.2.1 Gravity

The layout for modelling of the response of the repository to a gravity survey is simplified in the way that each separate deposition area is circumscribed by an individual sub-volume. The sub-volumes are divided in a deeper level circumscribing the canisters and an adjacent upper level circumscribing the deposition tunnels. The transport tunnels are kept as original 3D bodies from the construction design. The construction of these volumes is further described in Section 2.1. The volumes have been imported to the modelling program ModelVision ver.10, © Encom Technology, using an intermediate dxf-format.

The simplifications imply that the densities for different materials in the repository design have to be merged with the present bedrock properties to provide a weighted density for each sub-volume.

At first, for the canister sub-volumes, the average density for a deposition hole is calculated considering all material involved; canisters (two different fuels), ground plate and bentonite, Table 2-1. Secondly, the density of the deposition holes is weighted with the bedrock density in proportion to the occupied volume, giving an overall density for a sub-volume. The proportion of deposition holes in each sub-volume is very small and also similar, resulting in the same density for all sub-volumes, Table 2-2.

The densities for the deposition tunnels sub-volumes vary more, since the volume percentage of tunnels is higher. Table 2-3 shows the resulting densities calculated for each sub-volume. The weight contribution from reinforcement in the tunnels is very small and does not contribute to a higher density.

For modelling of the transport tunnels the real geometries are used and hence, no weighting or sub-volumes are necessary. The density in the tunnels is 1,900 kg/m³, same as for the Milos bentonite.

Table 2-1. Calculation of densities for individual deposition holes with two different fuel types, input data from /SKBdoc 1217234/. The resulting densities marked in yellow are further used in the calculation for the canister sub-volumes, Table 2-2.

Type	Diametre [m]	Length [m]	Volume [m³]	Weight_ Low [kg]	Weight_ High [kg]	Density_ Low [kg/m³]	Density_ High [kg/m³]	Comment
Canister_PWR	1.05	4.835	4.187	26,530	26,850	6,337	6,413	PWR with fuel
Canister_BWR	1.05	4.835	4.187	24,610	24,730	5,878	5,907	BWR with fuel
Deposition hole (bentonite only)	1.75	7.82	18.809	37,619	37,619	2,000	2,000	Bentonite MX80
Ground plate	1.75	0.18	0.433	1,278	1,278	2,952	2,952	
Deposition hole *without* canister PWR and ground plate			14.623	29,245	29,245	2,000	2,000	
Deposition hole *without* canister BWR and ground plate			14.623	29,245	29,245	2,000	2,000	
Deposition hole *with* canister PWR and ground plate			19.242	57,053	57,373	2,965	2,982	PWR with fuel
Deposition hole *with* canister BWR and ground plate			19.242	55,133	55,253	2,865	2,871	BWR with fuel

Table 2-2. Calculation of densities for the canister sub-volumes. Within the applied accuracy, all sub-volumes receive the same density.

Unit	Percentage by volume	Density_ Low [kg/m³]	Density_ High [kg/m³]
Deposition hole	0.9%	2,865	2,982
Surrounding bedrock (metagranite 101057)	99.1%	2,656	2,656
Canister sub-volumes	–	2,658	2,659

Table 2-3. Density calculated for each deposition tunnel sub-volume. In each sub-volume, the remaining volume is kept by metagranite with density 2,656 kg/m³.

Deposition tunnel sub-volume	No of tunnels	Total length [m]	Percentage by volume	Sub-volume density [kg/m³]
DA_East	12	2,905	10.5%	2,577
DA_West	11	2,450	10.6%	2,576
DB_East	14	2,850	9.6%	2,583
DB_West	6	1,154	11.3%	2,570
DB_South	39	11,152	10.1%	2,580
DC_North	41	11,015	9.9%	2,581
DC_South	44	11,576	10.1%	2,579
DD_North	40	10,619	9.9%	2,581
DD_South	40	11,148	9.8%	2,582

2.2.2 Magnetics

The modelling of the response of the repository to a magnetometry survey uses the same principals and models as described for gravity, Section 2.2.1. However, for modelling of the individual canisters, these objects have been replaced by vacuum in the sub-volumes used in ModelVision and the magnetic response has in exchange been calculated from magnetic dipoles. Finally the two responses have been added.

The magnetic volume susceptibility of each sub-volume was estimated by calculating the total susceptibility contribution of each material respectively, and then dividing the resultant total susceptibility with the volume of the model body.

For the canister sub-volumes, the magnetic susceptibility for a deposition hole is 0 SI considering the bentonite characteristics and the fact that the canister in this phase of the modelling is replaced by vacuum, Table 2-4. Weighting this susceptibility with the bedrock susceptibility gives an overall susceptibility for a sub-volume. The proportion of deposition holes in each sub-volume is very small and also similar resulting in the same susceptibility for all sub-volumes, Table 2-4.

Table 2-5 shows the resulting susceptibilities calculated for each deposition tunnel's sub-volume. The susceptibility contribution from reinforcement is evenly distributed according to tunnel length. The magnetic susceptibility for all sub-volumes are very similar and hence, a susceptibility average of 0.00363 SI has been used for all deposition tunnel sub-volumes.

Table 2-4. Calculation of magnetic susceptibility for the canister sub-volumes. Within the applied accuracy, all sub-volumes receive the same susceptibility.

Unit	Percentage by volume	Susceptibility [SI]
Bentonite MX80	–	0
Deposition holes (filled with bentonite and canister replaced by vacuum)	0.9%	0
Surrounding bedrock (metagranite 101057)	99.1%	0.004
Canister sub-volumes	–	0.00396

Table 2-5. Magnetic susceptibility calculated for each deposition tunnel sub-volume. In each sub-volume, the remaining volume is kept by metagranite with susceptibility 0.004 SI.

Deposition tunnel sub-volume	No of tunnels	Total length [m]	Percentage by volume	Sub-volume susceptibility [SI]
DA_East	12	2,905	10.5%	0.00362
DA_West	11	2,450	10.6%	0.00362
DB_East	14	2,850	9.6%	0.00365
DB_West	6	1,154	11.3%	0.00359
DB_South	39	11,152	10.1%	0.00364
DC_North	41	11,015	9.9%	0.00364
DC_South	44	11,576	10.1%	0.00364
DD_North	40	10,619	9.9%	0.00364
DD_South	40	11,148	9.8%	0.00365
Average for all sub-volumes				0.00363

For modelling of the transport tunnels the real geometries are used and hence, no weighting or sub-volumes are necessary. The magnetic susceptibility is 0.00040 SI based on the bentonite having susceptibility 0 SI and a small contribution from the reinforcement.

2.2.3 Reflection seismics

In principle a full modelling of the reflection seismic response in 3D would require large computational power to be handled realistically. In order to make the problem tractable, it was chosen to carry out modelling of the repository response in 2D. The geometry of the 2D model was chosen so that a seismic profile would pass over the deposition tunnels perpendicular to their strike. This is a reasonable 2D approximation since the tunnels are relatively long compared to their depth. However, since they are not infinitely long, the seismic response is overestimated in the 2D modelling.

2.2.4 TEM

The modelling of TEM is very calculation intensive. The modelling has been carried out with a finite element program that uses a regular mesh to describe the subsurface. It was necessary to make the node separation in this mesh larger than the width and height of the tunnels in the repository. A simplified model was constructed and the model blocks corresponding to tunnels were assigned a resistivity that was adjusted so that the resistance per length unit was the same as for the real bentonite-filled tunnels in the repository.

2.2.5 Induced polarization and resistivity

The modelling of the response of the repository to induced polarisation and resistivity surveys uses the same basic models and geometries as described for gravity and magnetics, Section 2.2.1 and 2.2.2. From these models, located in ModelVision, a voxel model is constructed for use in the inversion programme DCIP3D by UBC, University of British Columbia. This means that each voxel is assigned a resistivity or IP parameter depending on if the voxel is mainly inside or outside a current sub-volume in the construction layout, Figure 2-4 and 2-5. The parameters assigned are provided in Table 2-6.

A fine voxel mesh, 10×10 m horizontally and 5 m vertically, is assigned covering the repository volume, Figure 2-4. By this most of the voxels within this repository volume will match the contents within the repository. An even finer mesh will give very large computation times and/or memory problems running the software. Outside the repository volume padding cells have been added horizontally. Two basic resistivity models have been used, one with saline groundwater at depth and lower bedrock resistivity, similar to the TEM modelling, Section 2.2.4, and another using bedrock resistivity from petrophysics, Section 3.1 and no saline groundwater. The response both with and without the repository has been tested. Modelling has been carried out along a south-north profile, 1631600, Figure 2-4.

Table 2-6. Parameters used for modelling of the repository to a resistivity and/or induced polarisation survey.

Unit	Resistivity [ohmm]	IP [unit less]	Depth interval [m]	Depth resolution [m]
Surface layer	500	0	0–10	10
Transport tunnels	3	1	450–480	5
Deposition tunnels sub-volume	30	0.75	450–480	5
Canister sub-volume	1,000	0.37	450–480	5
Bedrock*	3,000 and 14,482	0.25	10–1,500	In general, 50 m above the repository and 100–300 m below
Saline groundwater at depth*	800	0	800–1,500	100–300 m

*These parameters are varied in the resistivity models used.

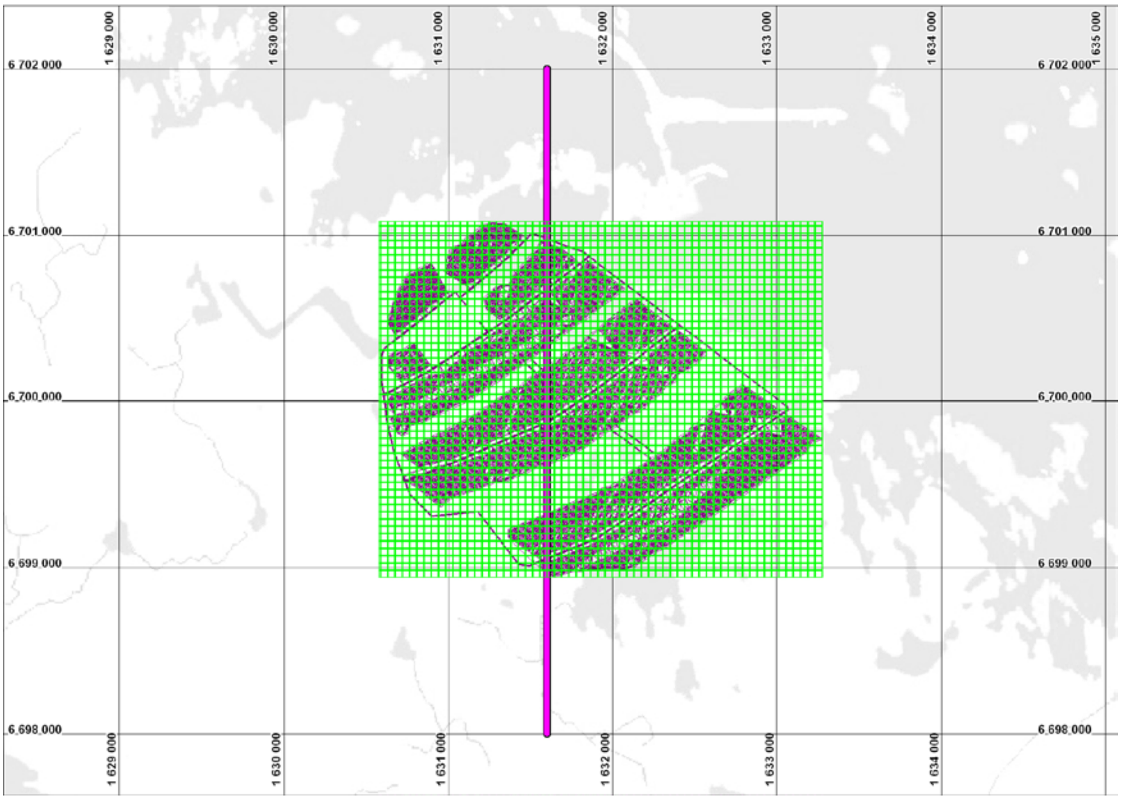

Figure 2-4. The surface projection of the repository model at Forsmark. The green mesh shows the horizontal extension of the finest voxel core used in the resistivity and induced polarization modelling. The profile in magenta shows the extension of the pseudo section along which the modelling has been carried out.

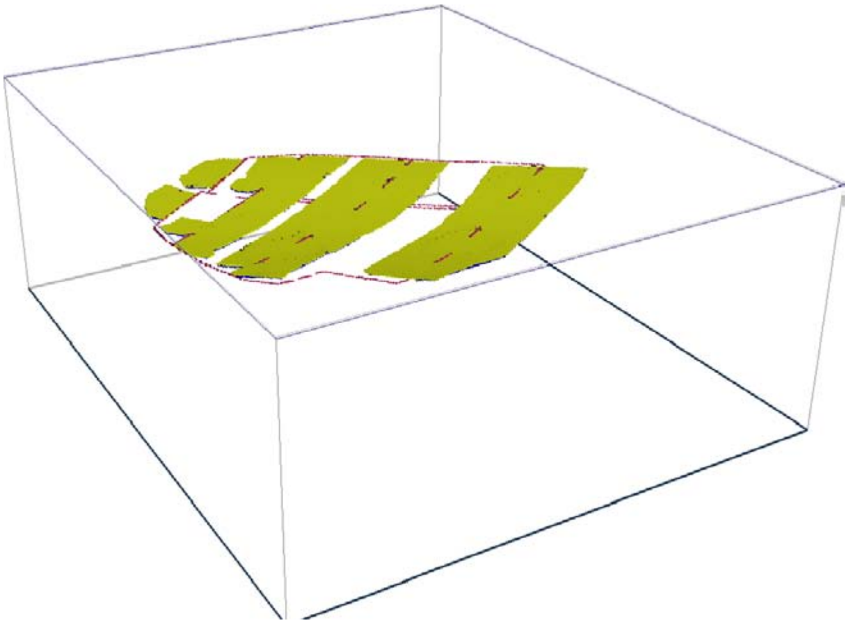

Figure 2-5. *The repository representation in the voxel model mesh, seen from south-west.*

3 Results

3.1 Physical properties of materials

Physical properties of selected materials were used as input parameters in the modelling work. The parameters were determined from literature studies (SKB reports and scientific papers) and from direct measurements on samples. The measurements were performed at the Petrophysical Laboratory of Luleå University of Technology (LTU). The selection of the different materials to use in the modelling work was made in co-operation between the participants of the modelling group and SKB, and was made with the aim to include the major bulk (or weight) part of materials in a future repository. The selection of physical properties to be determined was made with reference to state of the art mineral prospecting techniques.

A list of the physical properties of the selected materials is presented in Table 3-1 (note that the table is presented in two parts). The list of Table 3-1 contains data value, reference(s) and a short comment for each parameter, respectively. Table 3-1 includes the following materials:

Shotcrete (including reinforcement fibres). Samples from Äspö HRL were delivered by SKB, Leif Stenberg.

Reinforcement (rock bolts, wire mesh, fixing bolts). Two samples of standard 20 mm reinforcement bars were prepared by LTU.

Bentonite clay. All parameters come from literature studies. Samples of bentonite clay with correct water content could not be constructed and delivered to LTU

Canister. The complete canisters mainly consist of the materials cast iron, steel and copper. 4 samples of cast iron were prepared and delivered by the Canister Laboratory of SKB for determination of magnetic properties. The density of the canisters was estimated from literature studies.

Host rock, meta-granite to granodiorite. The dominant host rock at Forsmark is meta-granite to granodiorite. The petrophysical parameters of the rock have been reported in several studies during the site investigations.

Table 3-1. List of materials and their physical properties used in the modelling work.

Shotcrete (with reinforcement fiber)

	Data	Data source	Comment
Magnetic susceptibility	0.0077 SI	Measured at petrophysical laboratory of LTU.	Average value of 4 measurements on 4 samples, range 0.0053-0.0097 SI.
Natural Remanent Magnetisation	5,32 A/m	Measured at petrophysical laboratory of LTU.	Average value of 4 measurements on 4 samples, range 3.02-7.60 A/m.
Q-value (Mr/Mi)	16.7 SI	Calculated from NRM and magnetic susceptibility.	Average value of 4 measurements on 4 samples, range 11.7-22.2 SI.
Density	2,210 kg/m^3	Measured at petrophysical laboratory of LTU.	Average value of 4 measurements on 4 samples, range 2,080-2,310 kg/m^3.
Electric resistivity	21 Ohm-m	Measured at petrophysical laboratory of LTU.	Median value of 4 measurements on 4 samples, range 19-43 Ohm-m. Samples soaked for 48 hours in water with 3% NaCl.
Chargeability	0.38 (unit less)	Measured at petrophysical laboratory of LTU.	IP-effect chargeability **m.** Median value of 4 measurements on 4 samples, range 0.25-0.81. Samples soaked for 48 hours in water with 3% NaCl.

Reinforcement (bars or net)

	Data	Data source	Comment
Magnetic susceptibility	0.717 SI	Measured at petrophysical laboratory of LTU.	Average value of 2 measurements on 2 samples, range 0.715-0.718 SI.
Natural Remanent Magnetisation	31.20 A/m	Measured at petrophysical laboratory of LTU.	Average value of 2 measurements on 2 samples, range 28.40-33.99 A/m.
Q-value (Mr/Mi)	1.1	Calculated from NRM and magnetic susceptibility.	Average value of 2 measurements on 2 samples, range 1.1-1.2 SI.
Density	7,200 kg/m^3	/SKBdoc 1217234/.	Assumed to be same material as the cast iron of the canisters.
Electric resistivity	x	x	Not evaluated.
Chargeability	x	x	Not evaluated.

Bentonite clay

Magnetic susceptibility	x	x	Not evaluated.
Natural Remanent Magnetisation	x	x	Not evaluated.
Q-value (Mr/Mi)	x	x	Not evaluated.
Density	2,000 kg/m^3 (MX80) and 1,900 kg/m^3 (Milos bentonite).	/SKB 2009/.	MX80 will be used for fill in the canister holes and Milos-bentonite will be used as backfill of the tunnels.
Electric resistivity	3 Ohm-m	/SKB 2007, Rothfuchs et al. 2001/ .	Water content 21–22%.
Chargeability	See comment.	/Kiberu 2002, Saltas et al. 2008/.	No “single” value of IP effect of pure benonite at water content of 20% has been determined. With reference to the referred literature it is estimated that IP-bentonte/IP-granite is approximately 4/1

Canister (cast iron part)

Magnetic susceptibility	0.738 SI	Measured at petrophysical laboratory of LTU.	Average value of 4 measurements on 4 samples, range 0.736-0.739 SI.
Natural Remanent Magnetisation	3.55 A/m	Measured at petrophysical laboratory of LTU.	Average value of 4 measurements on 4 samples, range 2.57-6.00 A/m.
Q-value (Mr/Mi)	0.12	Calculated from NRM and magnetic susceptibility	Average value of 4 measurements on 4 samples, range 0.09-0.20 SI.
Density	Cast iron = 7,200 kg/m^3 Steel = 7,850 kg/m^3 Copper = 8,900 kg/m^3	/SKBdoc 1217234/.	
Electric resistivity	x	x	Not evaluated.
Chargeability	x	x	Not evaluated.

Meta granite-granodiorite (repository host rock)

Magnetic susceptibility	0.00388 SI	/Stephens et al. 2007/.	
Natural Remanent Magnetisation	0.026 A/m	Data not published.	Data were compiled during the work with /Stephens et al. 2007/, but were never included in the report.
Q-value (Mr/Mi)	0.163	Data not published. Calculated from NRM and magnetic susceptibility.	Data were compiled during the work with /Stephens et al. 2007/, but were never included in the report.
Density	2,656 kg/m^3	/Stephens et al. 2007/.	
Electric resistivity	14,482 Ohm-m	/Stephens et al. 2007/.	
Chargeability	6.5 mrad	Data not published.	Data were compiled during the work with /Stephens et al. 2007/, but were never included in the report.

3.2 Gravity

3.2.1 Response from the different alternatives

Modelling of the response of the repository to a gravity survey has been carried out using the program ModelVision ver.10, © Encom Technology.

The weighted average density for the canister sub-volumes are 2,658 kg/m³ compared to the background bedrock density 2,656 kg/m³. The low density of the MX80 bentonite in the deposition hole, 2,000 kg/m³, is to a large extent compensated by the heavy material in the canisters 2,865–2,982 kg/m³, Section 2.2.1.

The deposition tunnel sub-volumes have a more varied density distribution, 2,570–2,583 kg/m³, mainly due to the larger volume occupied by the tunnels in each sub-volume. The low densities of the Milos bentonite, 1,900 kg/m³ contribute to the low density and the metal within the planned rock reinforcement system would only give a minor density increase and is ignored in this case.

The transport tunnels are filled with Milos bentonite and hence has been assigned a density of 1,900 kg/m³.

The gravity response summed up from these three sub-volume types, calculated at the ground surface is presented in Figure 3-1. The maximum anomaly constitutes a gravity minimum of 0.009 mGal in the centre of the repository. From Figure 3-2 one can compare the modelled response with the actual gravity survey at Forsmark /Aaro 2003, Isaksson and Stephens 2007/. From this it is clear that the repository anomaly is less than 1% of the natural variation in the area. The shape of the repository anomaly is similar to the shape of the candidate metagranite unit and will give a very small contribution to the present gravity low caused by the granite and without divergent anomaly patterns.

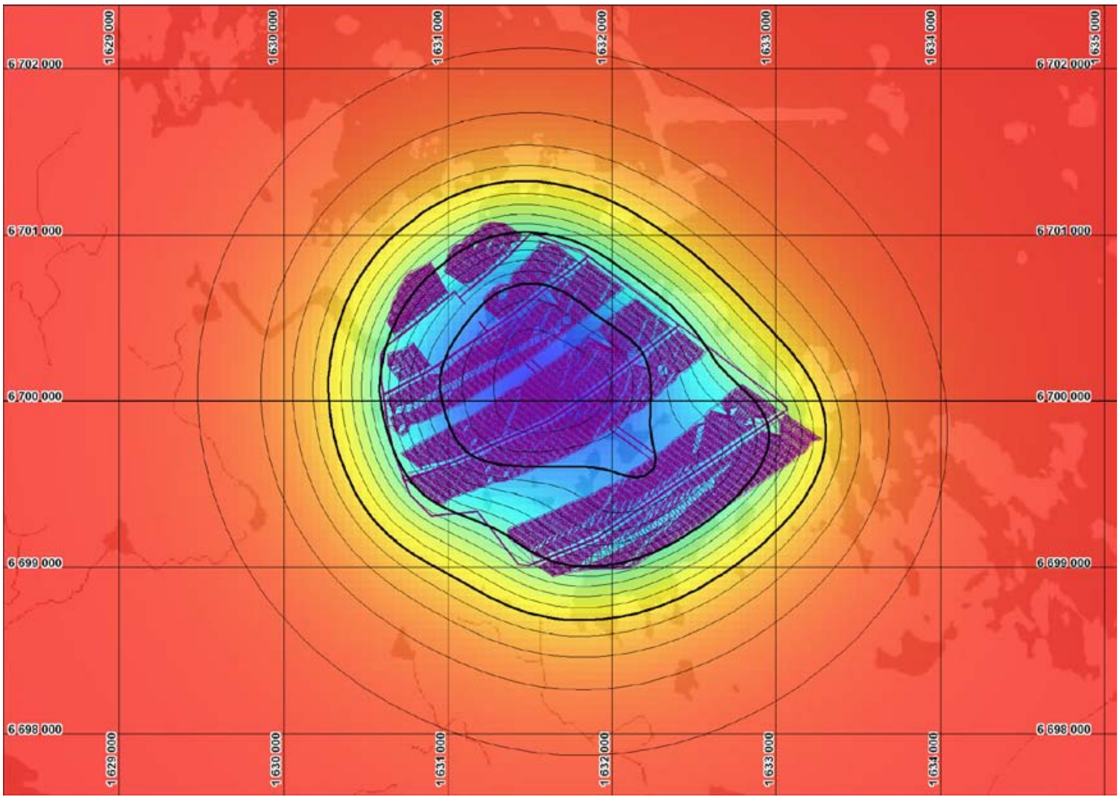

Figure 3-1. The repository gravity response [mGal] calculated at the ground surface in colour with black 0.0005 mGal contours, thicker lines each 0.0025 mGal.

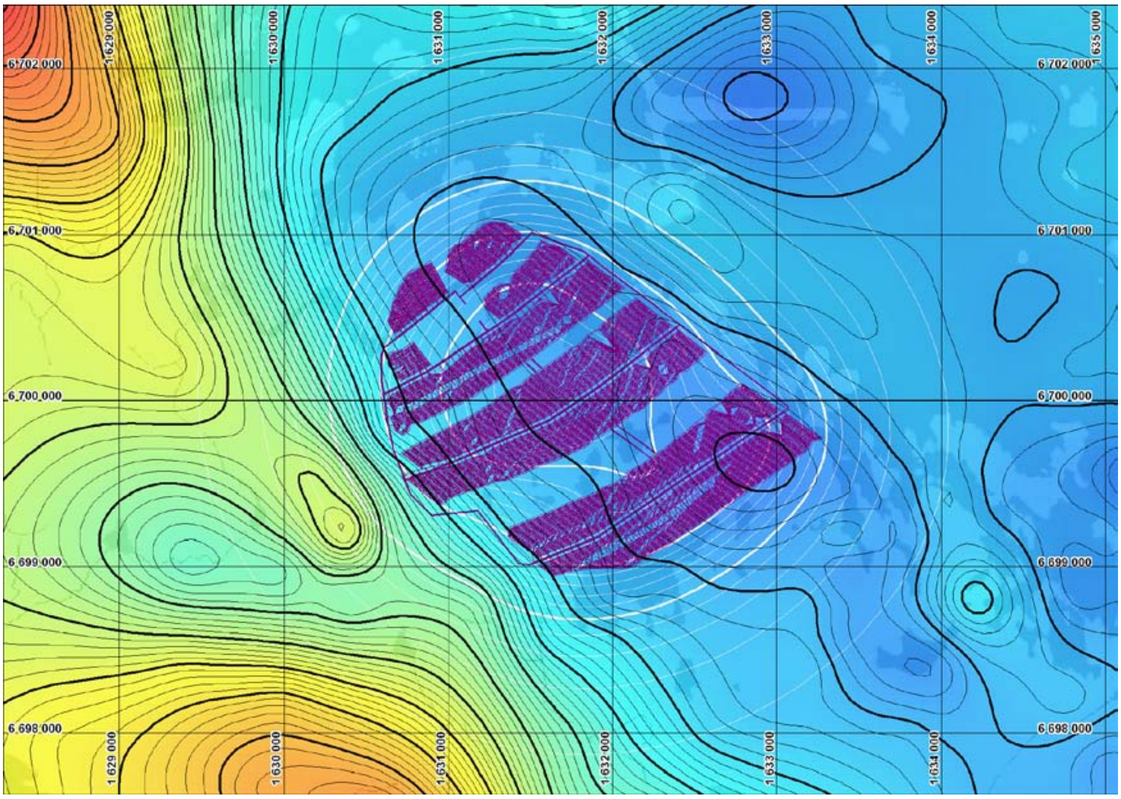

Figure 3-2. The present Bouguer anomaly at Forsmark in colour [mGal] with black 0.1 mGal contours, thicker lines each 0.5 mGal. The repository gravity response from Figure 2-1 is superimposed with white contours and thick lines each 0.0025 mGal.

3.2.2 Signal/noise

The maximum anomaly constitutes a gravity minimum of only 0.009 mGal which is comparable to the noise level of modern gravity meters.

3.2.3 Uncertainties

The use of sub-volumes is a simplification and will, at surface, give a much more generalized anomaly pattern compared to the details that will emerge from the actual underground construction and layout. However, this effect diminishes rapidly with increased depth and considering the depth from surface to the repository this difference in anomaly pattern will be very small.

The parameters used for the repository sub-volumes and the background geology are uncertain.

How well the adapted model represents the actual repository geometry and layout is uncertain.

3.3 Magnetics

3.3.1 Response from the different alternatives

Modelling of the response of the repository to a magnetometry survey has been carried out using the program ModelVision ver.10, © Encom Technology and GeoVista in-house software for magnetic dipole modelling.

Background parameter for the modelling is a magnetic susceptibility 0.004 SI comparable to the metagranite properties, Section 3.1. The total intensity is 51,400 nT, inclination 73° and declination 0°, similar to today and with a rather steep inclination giving a strong anomaly response.

The magnetic susceptibility for the canister sub-volumes are 0.00396 SI, Table 2-4, very similar to the bedrock susceptibility of 0.00388 SI. The susceptibility of the MX80 bentonite in the deposition hole is very low, 0 SI, but the total volumes are negligible compared to the surrounding bedrock volume, giving only a small change in the weighted average. The responses from the actual canisters have been calculated separately, see below, and have no effect in the canister sub-volumes.

In the deposition tunnels, the Milos bentonite has a low magnetic susceptibility, 0 SI, and is mixed with 628.5 tonnes of iron from the planned rock reinforcement system giving a total magnetic susceptibility of 721.2 SI. These two materials are evenly distributed within a total tunnel volume of ca. 1.8 million m³, giving a total susceptibility of 0.00041 SI. A weighted average between the tunnels and the surrounding bedrock result in the deposition tunnel sub-volumes being assigned a magnetic susceptibility of 0.00363 SI.

The transport tunnels are filled with Milos bentonite and hence have been assigned a magnetic susceptibility of 0 SI.

Finally, the contributions from the actual canisters have been added from a magnetic dipole calculation. A vertical magnetization is assumed since the horizontal magnetization will be attenuated by demagnetization effects. The vertical magnetization was calculated based on the measured magnetic susceptibility of samples of the cast iron Table 3-1. Remanent magnetization was assumed to be soft and was added as vertical magnetization.

The magnetometry response summed up from these four contributions, calculated at the ground surface is presented in Figure 3-3. The maximum anomaly constitutes a magnetic span from –0.01 to 0.06 nT, in total a range of 0.0675 nT. From Figure 3-4 one can compare the modelled response with the present detailed magnetic ground survey at Forsmark /Isaksson et al. 2007/. The natural variation in this survey is around 1,200 nT and from this it is clear that the repository anomaly, in this geological environment can be considered as negligible. It is negligible also when taking into consideration possible future variations in the earth magnetic field intensity and orientation based on historical variations /Heller et al. 2002/. The shape of the repository anomaly is similar to the structural setting of the candidate metagranite unit and will give a very small contribution to the present magnetic anomaly field and without divergent anomaly patterns.

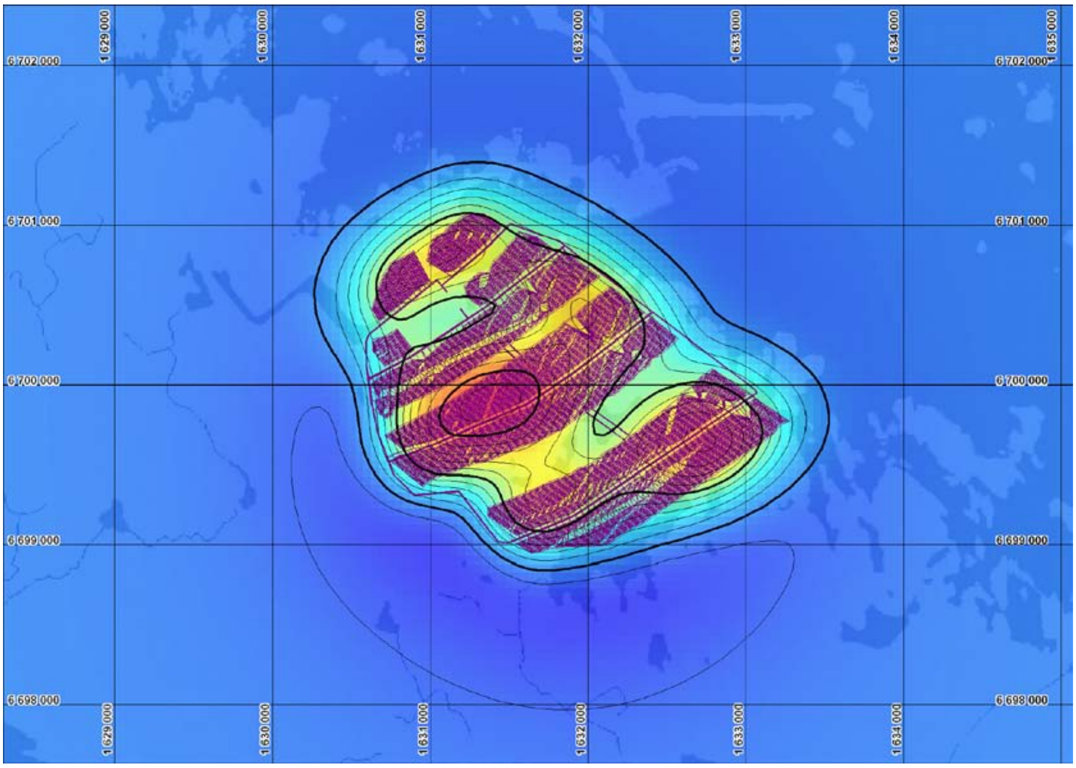

Figure 3-3. The magnetometry response from the repository [nT] calculated at the ground surface with black 0.005 nT contours, thicker lines each 0.025 nT.

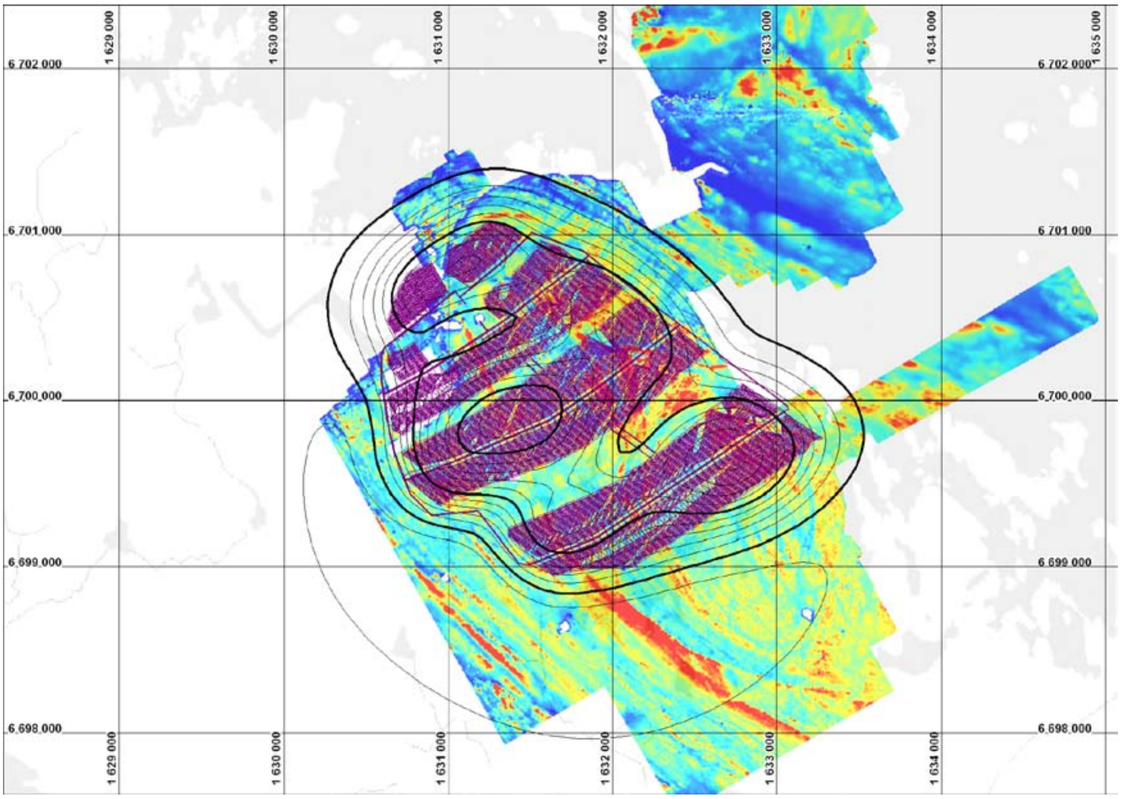

Figure 3-4. *The present magnetic total field anomaly at the ground surface in Forsmark in colour [nT]. The repository magnetometry response from Figure 3-3 is superimposed with black contours.*

3.3.2 Signal/noise

The maximum anomaly generated by the repository is 0.0675 nT, which is within the noise level of a modern magnetometer.

3.3.3 Uncertainties

The ambient magnetic flux intensity used in the modelling was 51,400 nT, inclination 73° and declination 0°, similar to the Earth magnetic field of today in Forsmark. The Earth´s magnetic field will over time show temporal variation with respect to both magnitude and direction. Such variations will affect both the induced magnetic field from waste canisters and reinforcement as well as the induced magnetic field from the host rock. The maximum possible induced magnetic field from the canisters will be for a vertical ambient field. However, the difference between such a situation and the modelled field is considered moderate. At present the earth magnetic field incliniation/intensity is c. 30°/30,000 nT at the equator and c. 90°/60,000 nT at the poles. Research investigations of historic variations of the earth magnetic field (paleomagnetic and paleointensity investigations) indicate that at different times during the past 10^4–10^5 years the intensity was 40% higher and 30% lower than the present intensity /Heller et al. 2002/.

A vertical magnetization has been assumed for the steel in the waste canisters. The elongated shape of the canisters will give larger demagnetization effect perpendicular to the canister axis compared to the parallel direction. However, the actual effect of demagnetization has not been calculated.

The use of sub-volumes is a simplification and will, at surface, give a much more generalized anomaly pattern compared to the details that will emerge from the actual underground construction and layout. However, this effect diminishes rapidly with increased depth and considering the depth from surface to the repository this difference in anomaly pattern will be very small.

The parameters used for the repository sub-volumes and the background geology are uncertain.

How well the adapted model represents the actual repository geometry and layout is uncertain.

3.4 Reflection seismics

The main purpose of this study was to calculate the reflection seismic response of the planned SKB repository at Forsmark. In particular, will it have any observable reflection seismic response at all? This is a complex 3D problem that requires large computational power to be handled realistically. In order to make the problem tractable, preliminary 2D seismic modelling has been performed. The main factors affecting the seismic response are (i) the geometry of the repository, (ii) the physical property contrasts between the back-fill and the host rock, (iii) the frequency content of the signal, and (iv) the signal to noise ratio (S/N) of the data. A seismic response will nearly always be observed on noise free data.

The geometry of the 2D model was chosen so that a seismic profile would pass over the deposition tunnels perpendicular to their strike (Figure 3-5). This is a reasonable 2D approximation since the tunnels are relatively long compared to their depth. However, since they are not infinitely long, the seismic response is overestimated in the 2D modelling. Velocities and density of the host rock are relatively well known from seismic measurements in the area. The bentonite density used was provided by SKB. There is little information on the seismic velocities of bentonite in the literature. However, /Marelli et al. 2010/ report values of 2,000 m/s and 500 m/s for Vp and Vs, respectively. These values are based on studies carried out for NAGRA in Switzerland. Relevant physical properties for all rocks and the bentonite used in this study are given in Table 3-2.

Table 3-2. Rock/material properties.

Rock/material	Vp (m/s)	Vs (m/s)	Density (kg/m^3)
Granite	5,500	3,200	2,600
Fracture zone	5,000	3,000	2,500
More mafic rock	5,900	3,400	2,700
Bentonite	2,000	500	2,000

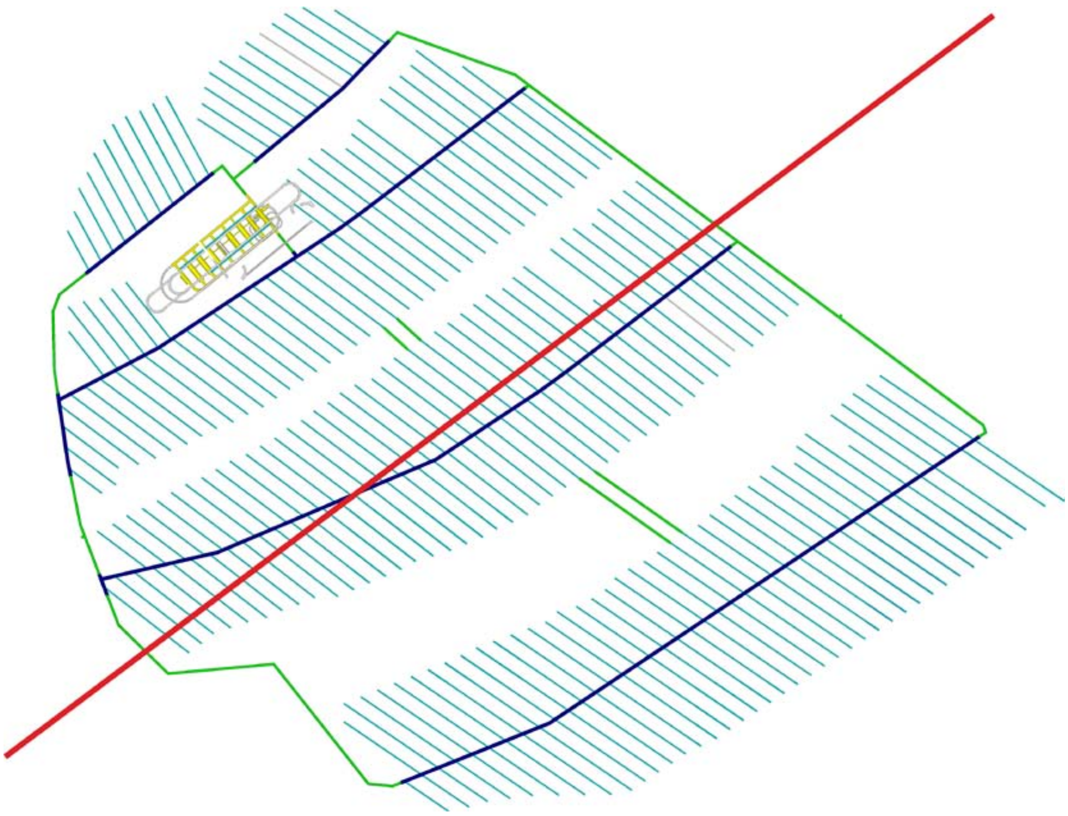

Figure 3-5. *Top view of the repository with a hypothetical surface seismic profile (in red) shown. It is approximately the deposition tunnel geometry (in light blue) that has been used for the seismic modelling.*

A simple model without the repository was first generated (model A) to investigate the baseline seismic response (Figure 3-6). As reference reflectors, a 10 m thick fracture zone was included in the model at 800 m depth and a step discontinuity to a more mafic rock at 1,000 m depth. The fracture zone reference reflector is included in the model since features such as this are observed clearly in the real data /e.g. Juhlin and Stephens 2006/. There is not a similar analogy for the transition to more mafic rock, but it is included since it is useful to have a simple step discontinuity in the model for calibration. The repository deposition tunnels are modelled as 4 m×4 m cross sections through the host rock (Figure 3-7). This areal cross section approximately correspond to the areal cross sections of the planned tunnels, but the actual dimensions differ somewhat. From a seismic modelling point of view it is the area which is important since the tunnels will act as point diffractors and the diffraction response will be proportional to areal cross section.

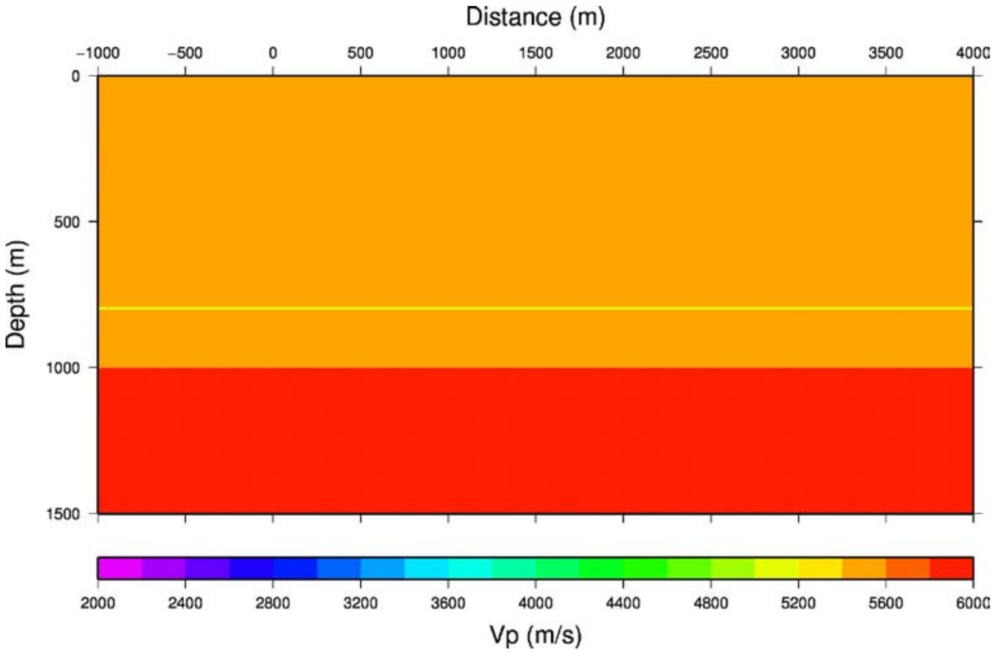

Figure 3-6. P-wave velocity distribution in model A.

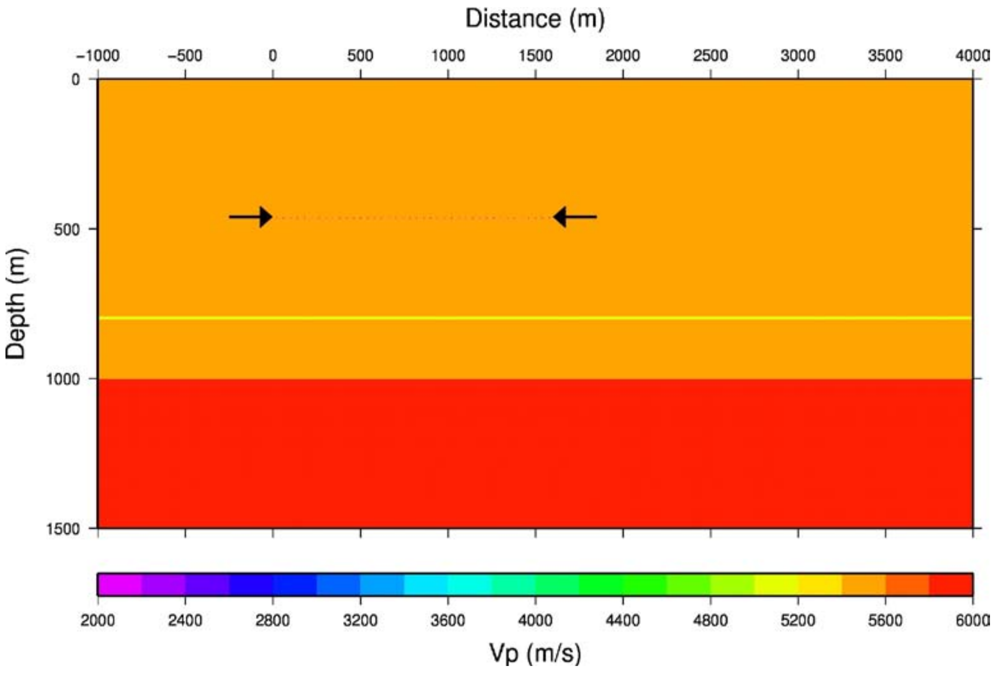

Figure 3-7. P-wave velocity distribution in model B. Arrows mark the location of the repository. A detailed view of the repository P-wave velocity model is shown in Figure 3-8.

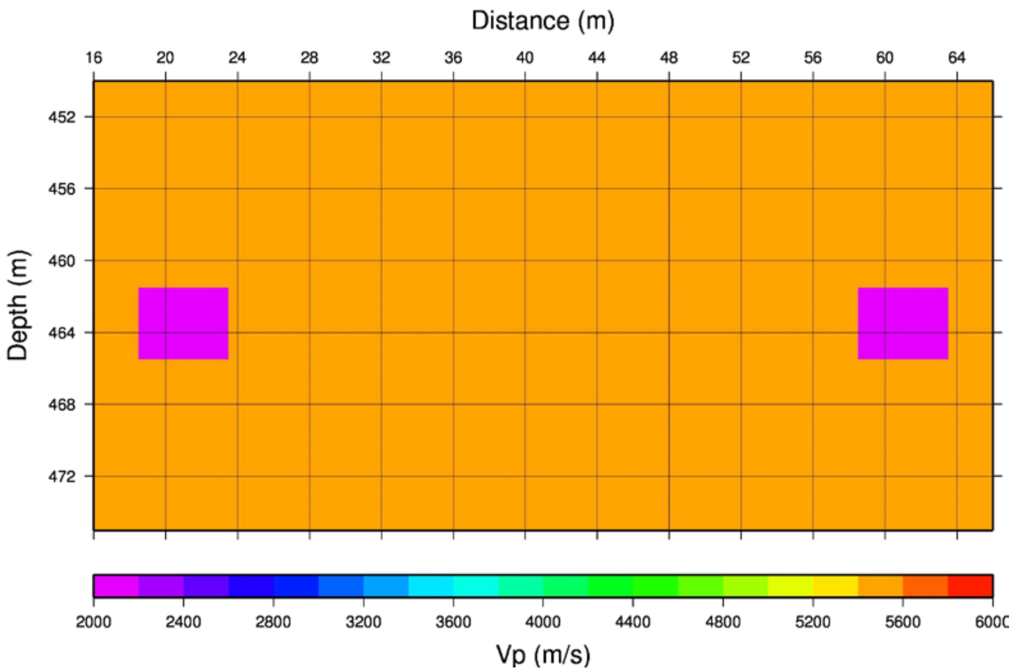

Figure 3-8. *Detailed view of the P-wave velocity distribution for model B. Velocities of 2,000 m/s correspond to bentonite.*

3.4.1 Seismic modelling

Synthetic seismic data were generated using the two models shown in Figures 3-6 and 3-7. Modelling parameters are given in Table 3-3. An elastic 2D finite difference modelling code was used that is available in Seismic Unix (www.cwp.mines.edu). The code is 4^{th} order in space and 2^{nd} order in time. A source wavelet with a dominant frequency of 120 Hz was used. This produces synthetic data with similar frequency content as the real data. Useful signals are present up to about 300 Hz. This gives wavelengths for the shear waves in the bentonite that are as short as about 2 m, implying about 2 points per wavelength for the shear waves in the bentonite using a 1 m grid spacing. With 4^{th} order differencing in space, normally a minimum of 5–10 samples per wavelength are required to avoid grid dispersion. However, the area containing these low velocities is very small and the major portions of the models have a shear wave velocity of 3,200 m/s, giving minimum wavelengths of about 10 m. Therefore, grid dispersion is relatively minor as a whole in the modelling. Going to a smaller grid spacing would make computation times too long.

Table 3-3. Modelling parameters.

Parameter	Model A	Model B
Grid spacing	1 m	1 m
Dominant frequency	120 Hz	120 Hz
Source wavelet	Gaussian derivative	Gaussian derivative
Time step	0.00025 s	0.00025 s
Attenuation in model (Q)	200	200
Number of shots	150	150
Shot spacing	20 m	20 m
Number of receivers	200	200
Receiver spacing	10 m	10 m

After generation of the synthetic seismic data, the data were scaled by dividing the sample values by the square root of time. This converts the geometric spreading of energy from 2D to 3D. Inspection of source gathers at this stage shows that the repository tunnels generate a distinctive diffraction pattern (Figure 3-9). Although uncorrelated noise levels are relatively low at Forsmark, noise was added to the synthetic data (Figure 3-10) to test if the diffraction pattern will be observed in the processed sections. Choosing the parameter sn=500 gives noise levels that are similar to the real data (Figure 3-11). A total of 150 sources gathers were generated for each model and then put into a processing stream. Computer time for generating these gathers is about 50 hours on a single processor standard PC.

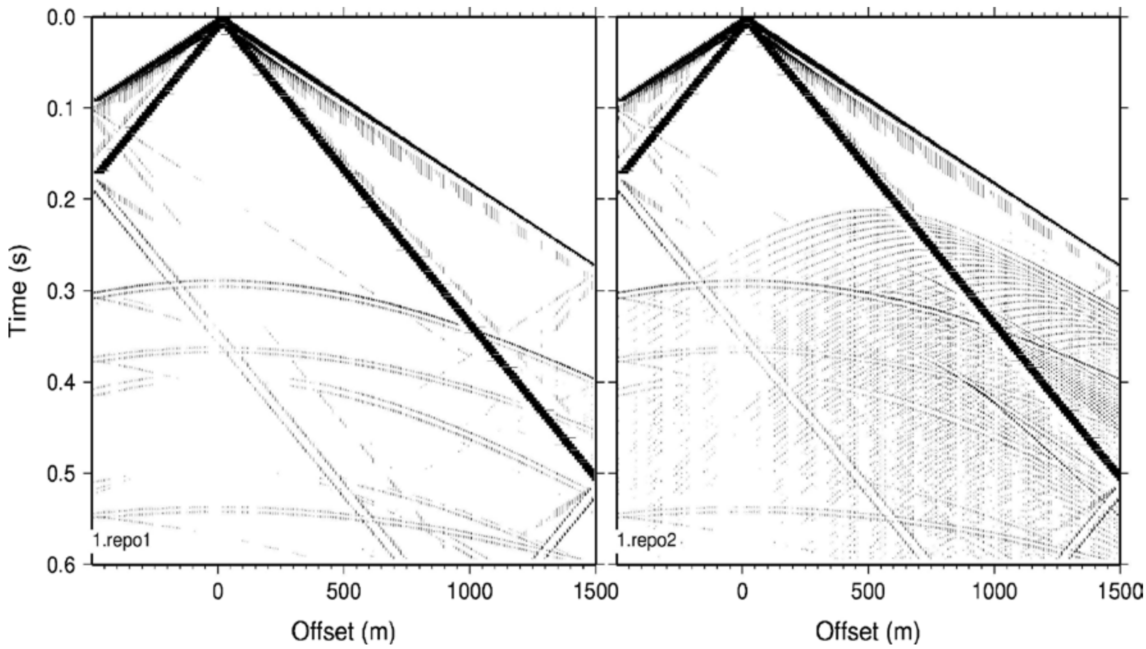

Figure 3-9. *Synthetic source gathers for source location x=–500 for model A (1.repo1) and model B (1.repo2). Note the distinctive diffraction pattern from the repository in model B. No noise has been added.*

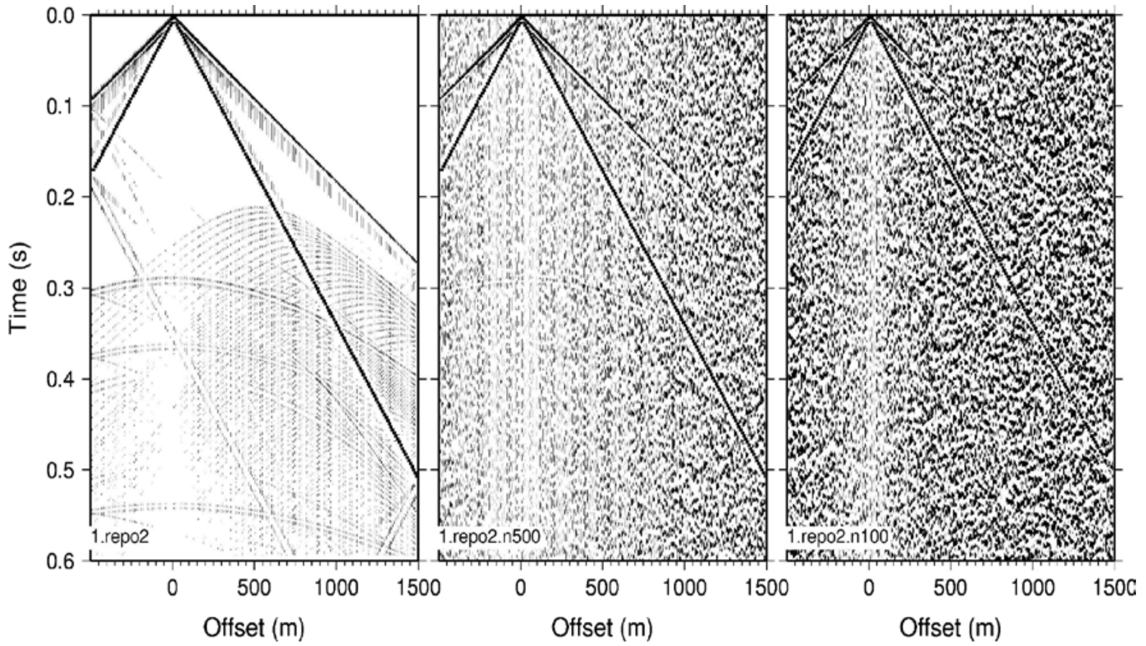

Figure 3-10. *Synthetic source gathers for source location x=–500 in model B with no noise, sn=500 and sn=100. The noise added was limited to the frequency band 10–20–100–150 Hz.*

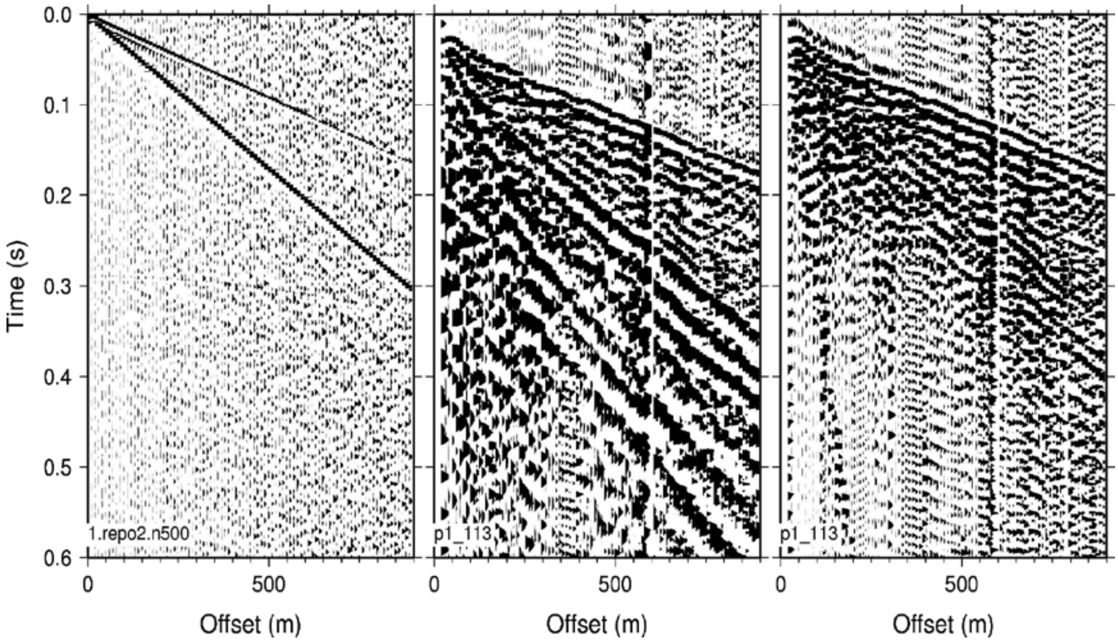

Figure 3-11. *Synthetic source gather with noise added compared to a source gather from the real data. The middle panel is a typical source gather from profile 1 in the Forsmark area. The rightmost panel shows the same source gather filtered in the band 30–60–180–270 Hz.*

3.4.2 Processing

Processing was kept simple and consisted of CDP sorting and application of automatic gain control (AGC) and normal moveout (NMO) to each of the data sets (Table 3-4). The parameters used for AGC and NMO are similar to those that have been applied to the real data acquired in the area. Figures 3-12 and 3-13 show stacked and depth converted migrated sections, respectively, for model A. Figures 3-14 and 3-15 show stacked and depth converted migrated sections, respectively, for model B.

3.4.3 Response from the different alternatives

As expected, both the fracture zone and step discontinuity are clearly observed in the two models (Figures 3-13 and 3-15) at 800 m and 1,000 m. In model B, the repository also shows a clear seismic response at about 460 m depth (Figure 3-15). Even though the tunnels are spaced far apart relative to their width, they produce a near sub-horizontal reflection. This reflection is not as sharp as the fracture zone or step discontinuity reflection. Instead, it has an undulating pattern to it with some tails following the main reflection surface. These tails are probably due to converted shear waves that have not stacked in properly with the processing velocities used. Regardless, with the given geometry, velocity contrasts, assumed noise levels and signal frequency, the seismic response of the repository cannot be missed.

3.4.4 Signal/noise

Although uncorrelated noise levels are relatively low at Forsmark, noise was added to the synthetic data (Figure 3-10) to test if the diffraction pattern will be observed in the processed sections. Choosing the parameter sn=500 gives noise levels that are similar to the real data (Figure 3-11).

3.4.5 Uncertainties

The main uncertainty in the modelling is the assumed seismic velocities of the bentonite. If the true velocities are higher, then the seismic response will be weaker. However, even if the P-wave velocity and S-wave velocity are off by 1,000 m/s, there is still is a significant contrast present. A P-wave velocity of 3,000 m/s and an S-wave velocity of 1,500 m/s would probably still generate an observable response. It would be useful to get better control on the bentonite velocities before more modelling is done.

Table 3-4. Processing parameters.

Step	Process	Parameters
1	CDP sort	
2	Automatic gain control	Window=50 ms
3	Normal MoveOut	v=5,500 m/s, stretch=40%
4	Stack	
5	Stolt migration	v=5,500 m/s
6	Depth conversion	v=5,500 m/s

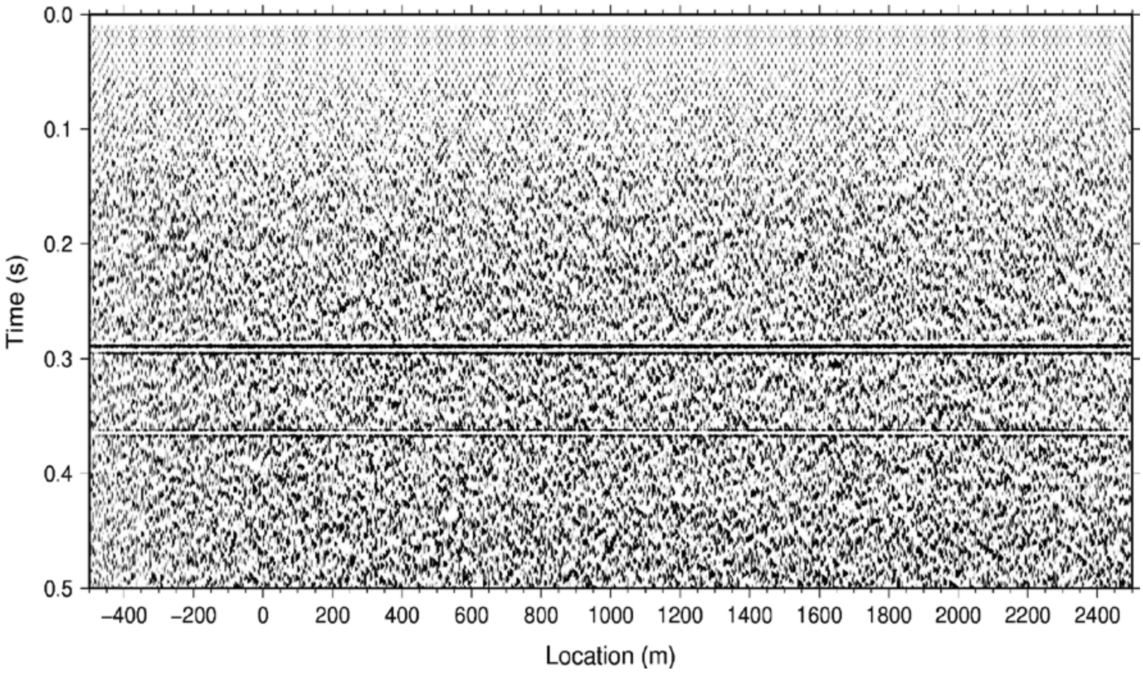

Figure 3-12. *Stacked section with noise added: Model A.*

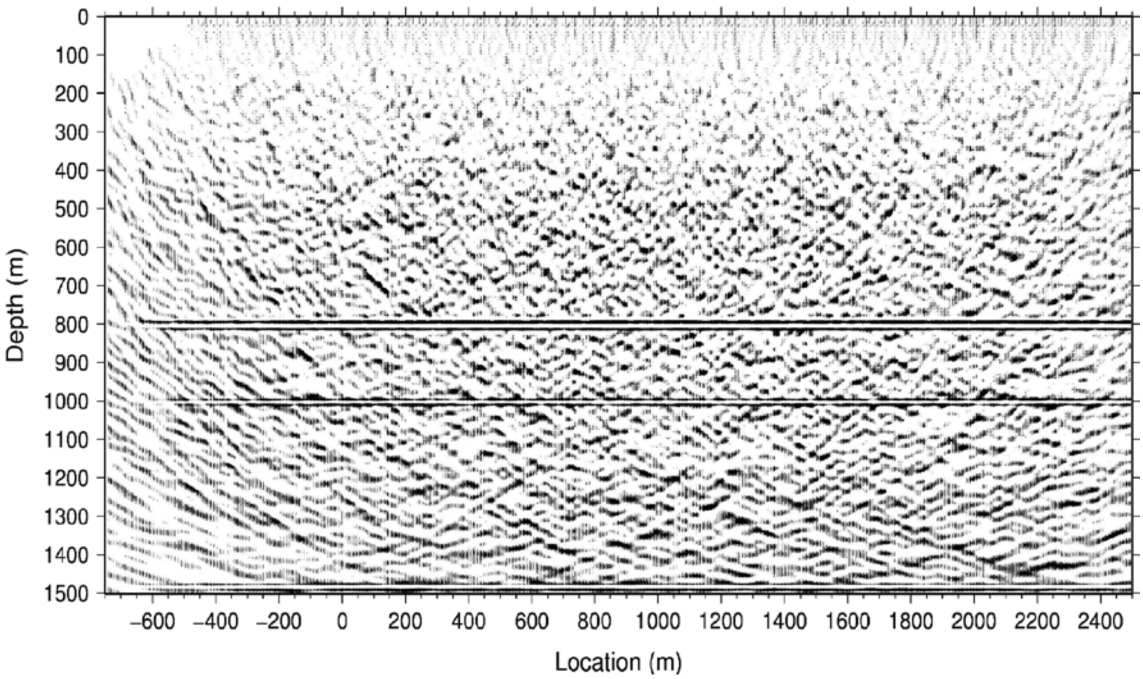

Figure 3-13. *Depth converted migrated section with noise added: Model A.*

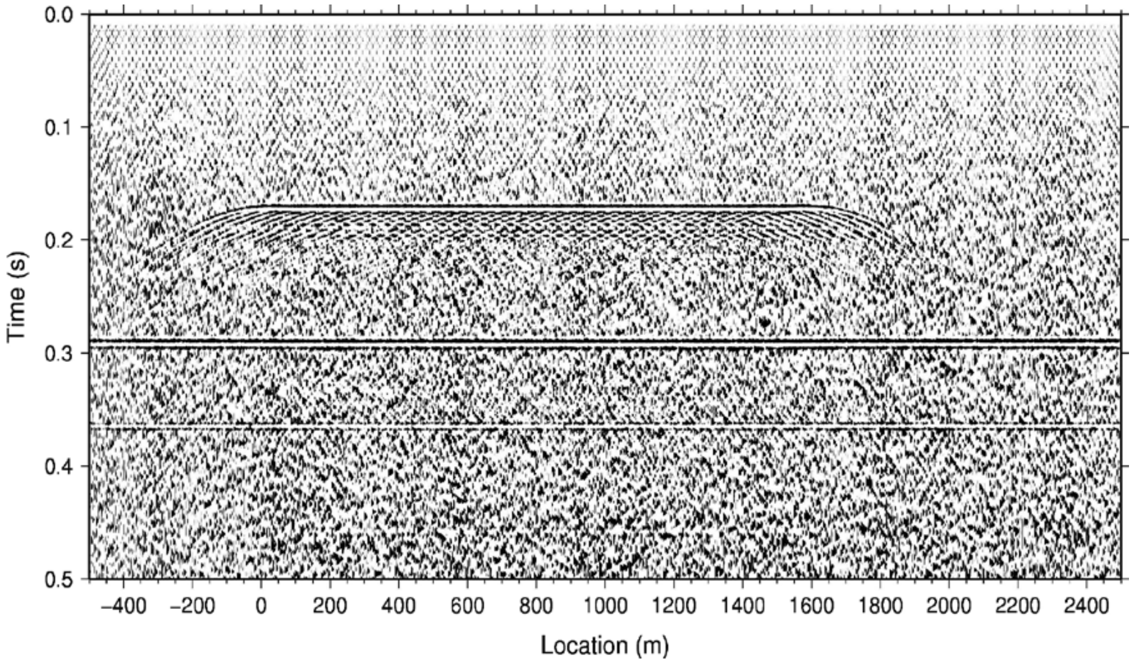

Figure 3-14. Stacked section with noise added: Model B.

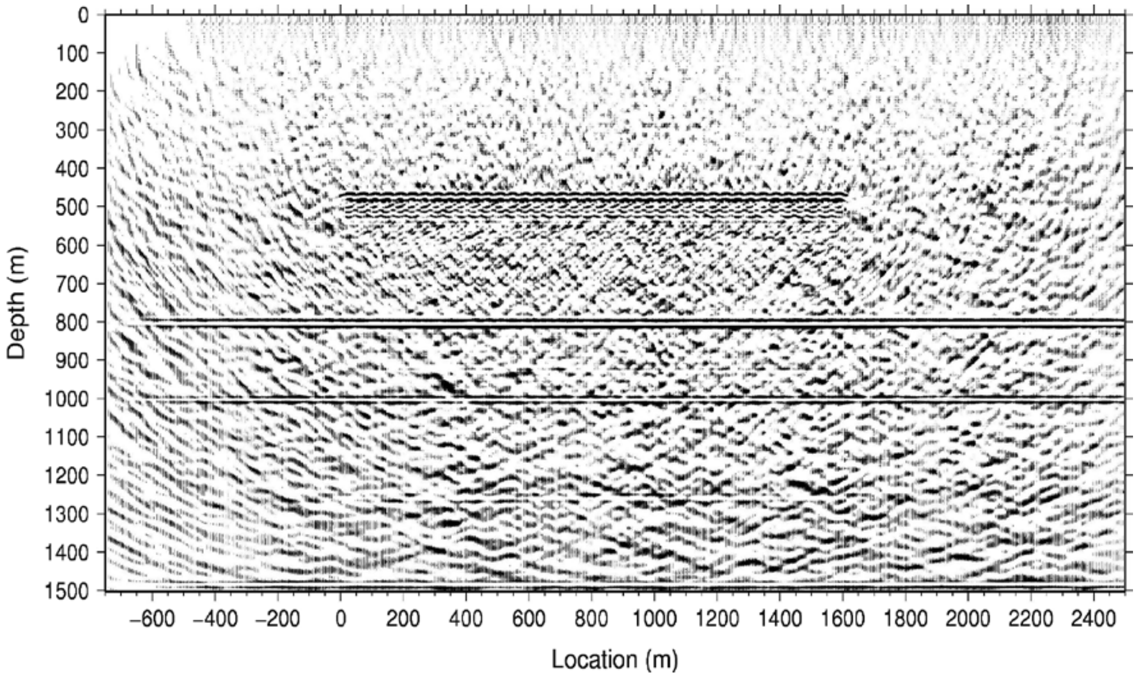

Figure 3-15. Depth converted migrated section with noise added: Model B.

3.5 TEM

Modelling of the response of the repository to a Transient Electromagnetic (TEM) survey system has been performed. The modelled survey setup has been a large fixed loop transmitter (1,000 by 1,000 metres) and a magnetic dipole receiver of induction coil type. This setup is analogous to what is used with commercial systems for base metal exploration used in the exploration industry today like Geonics Protem, Zonge and TerraTEM. Survey parameters have been chosen as they would be for a survey aiming at identifying a deep-seated mineralization in an exploration programme.

Modelling has been performed with the program Loki which is a part of the P223 suite of EM modelling software from Csiro/Amira, Australia. The program is capable of modelling more or less arbitrary resistivity distributions by dividing the sub-surface into a finite element mesh. Each cell in the mesh can be assigned an individual electric resistivity. The calculations are very processor intensive and it has therefore not been practically possible to model the repository geometry in detail. A simplified version of the repository has therefore been used with 50×50×50 metre large cells in the repository volume (Figure 3-16). Larger padding cells have been added outside the central volume so that the model has a total size of 4,200×4,200×1,900 metres. Each model took around 10 hours to calculate on a standard PC computer.

The resistivity of model cells that correspond to bentonite filled volumes has been modified so that the cross-sectional resistance of a tunnel per unit length is unchanged. These cells therefore have a resistivity of 70 Ωm in the model. The response for a model with a resistivity of 40 Ωm for the tunnel cells has also been calculated. The EM response for a low-resistivity target at depth is strongly dependent upon the size of the target, i.e. the induced eddy current paths should be long. The bentonite filled tunnels form closed or semi-closed loops that potentially can give strong EM responses. The canisters are very small in comparison and are therefore not expected to give a strong EM response, in spite of their very low resistivity and large number.

The surrounding bedrock has been assigned electric properties based on modelling of TEM soundings at Forsmark performed within the site investigation /Thunehed and Pitkänen 2007/. Bedrock resistivity was assigned to 3,000 Ωm in volumes with brackish groundwater and 800 Ωm in volumes with salt groundwater (Figure 3-16). The brackish groundwater is present down to 900 metres depth and deeper levels are saturated with salt water. A thin surface layer corresponding to moraine has been added on the top (10 m, 500 Ωm).

3.5.1 Response from the different alternatives

The model response of the repository can be compared with the response of the corresponding rock volume without the repository present (Figure 3-17). The example is for a transmitter loop positioned above the centre of the repository and with a receiver in the centre of the transmitter loop.

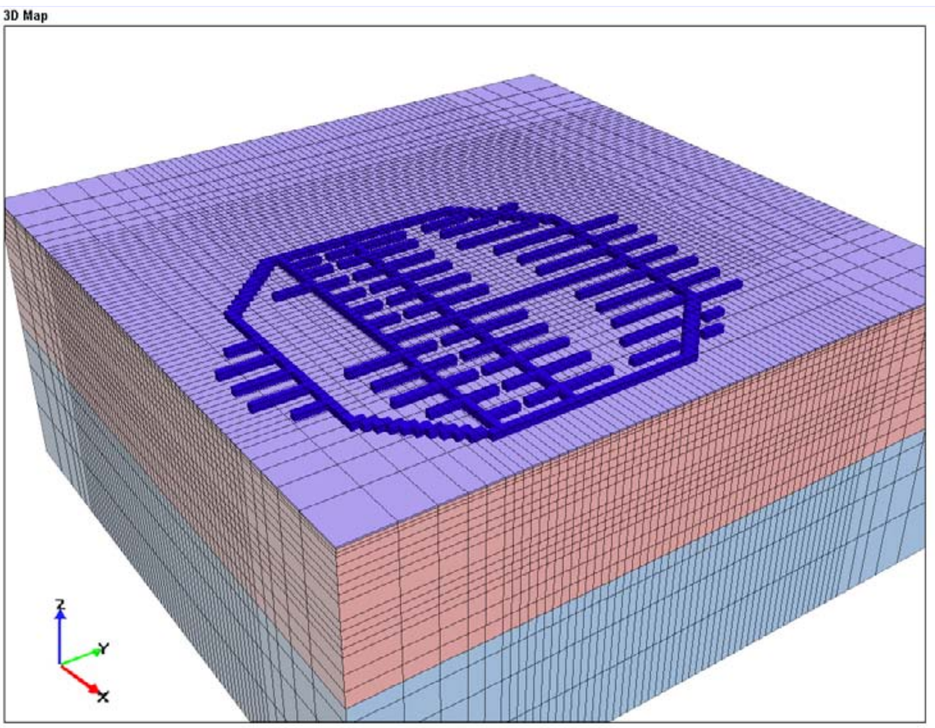

Figure 3-16. 3D view of the TEM model. It consists of a ring-formed tunnel and a number of side tunnels that conceptually resemble the true repository model. The cross-sectional area of the tunnels in the TEM model is however considerably larger due to limitations in the available modelling software.

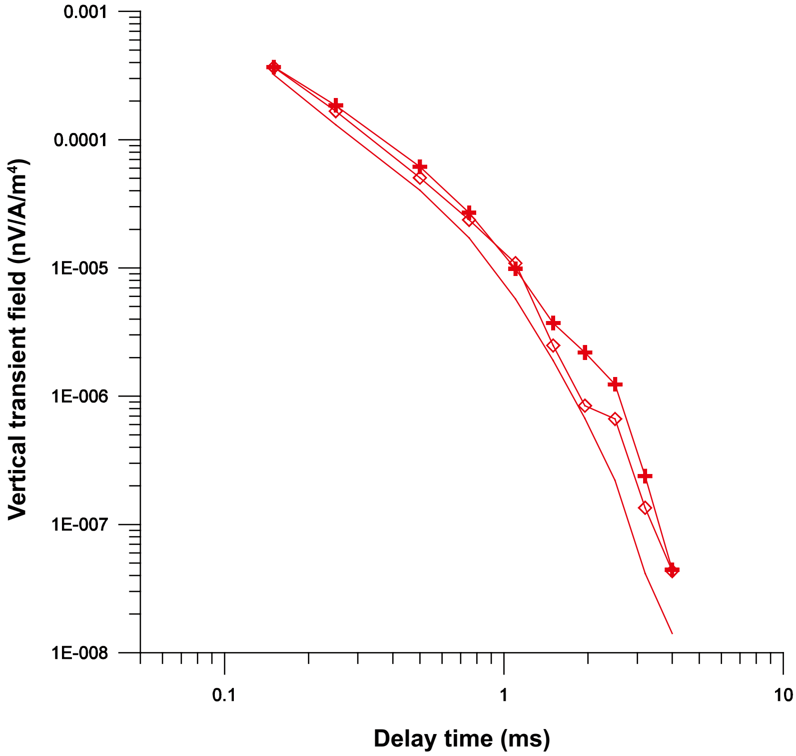

Figure 3-17. *Transient decay calculated for a receiver position on the ground surface above the centre of the repository. The curve with diamond symbols represents a model with 70 Ωm model cells for the repository tunnels. The curve with crosses represents a model with 40 Ωm model cells for the tunnels. The curve without symbols represents a model without any repository present.*

The large lateral extent of the repository in combination with the large depth makes the lateral wave-length of EM anomalies due to the repository quite large. The signal decay is quicker than expected after around 1 ms. This is probably because the model volume is small compared to the diffusion depth of the EM field at such late times. The signal strength is probably underestimated for this reason. There is also a lack of smoothness in the decay curves after 1 ms, indicating a limitation in the software precision at these late delay times.

The calculated secondary field for the vertical component is approximately twice as high with the repository present at late time gates and less at early time gates. The late time signal ratio corresponds to a ratio of apparent resistivity of 1:1.6 with and without the repository present. The repository would thus, in principle, be detectable with a TEM system.

3.5.2 Signal/noise

The increase in the secondary TEM field due to the presence of the repository is clearly within the detection limit of present day TEM systems. The noise level at late time gates is around 10^{-7} to 10^{-6} nV/A/m^4. Resistivity variations are however quite large in barren crystalline rock. Figure 3-18 shows an example from a TEM sounding performed within the site investigation at Forsmark /Thunehed and Pitkänen 2007/, where several receiver positions were measured with the same transmitter loop. The measurements were performed close to Storskäret, not far from the planned repository. The variations in signal magnitude are comparable to the difference in the modelling results for models with and without the repository present.

Figure 3-19 shows results from different sounding locations around Forsmark. The soundings were performed at Storskäret, Eckarfjärden and Bersbo, all within around 6 km of the planned repository. The variations in signal magnitude are significantly larger than the effect of the repository.

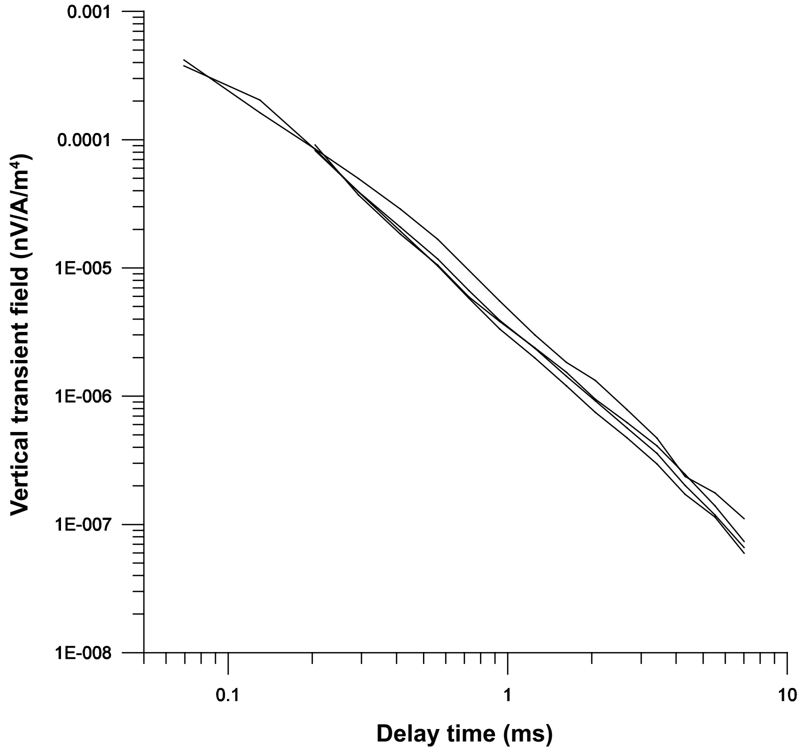

Figure 3-18. *Transient decay recorded at four different receiver positions at Storskäret /Thunehed and Pitkänen 2007/. The same transmitter loop was used for all measurements. The delay time refers to the time after current shut-off in the transmitter loop.*

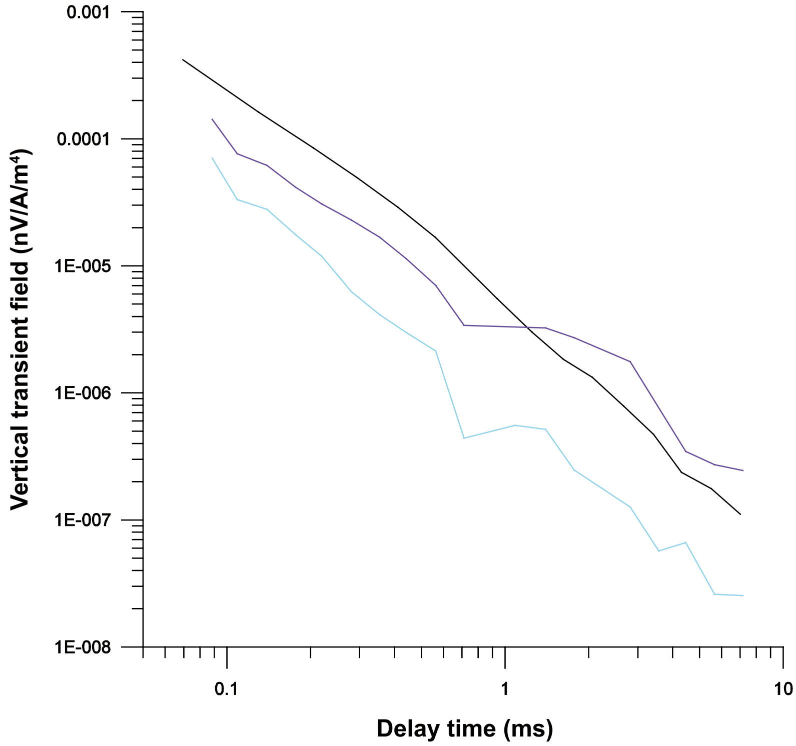

Figure 3-19. *Transient decay recorded at three different locations within around 6 km of the planned repository /Thunehed and Pitkänen 2007/. The locations are at Storskäret (black line), Eckarfjärden (purple) and Bersbo (cyan). Different transmitter loops were used for the measurements. The delay time refers to the time after current shut-off in the transmitter loop. The soundings at Eckarfjärden and Bersbo are affected by anthropogenic noise.*

The natural resistivity variations in granitoid rocks may be of at least one order of magnitude. Such variations are due to local variations in fracturing, porosity, pore space texture and pore water salinity. It is therefore hardly likely that a minor, although measurable, change in apparent resistivity would be interpreted as a possible mineralization at depth.

3.5.3 Uncertainties

It has not been practically possible to model the repository geometry in detail. Instead, a simplified model with adjusted resistivity has been used. However, the response of the repository is not very strong even if a lower than expected effective resistivity of the tunnels is used (Figure 3-17).

The EM response of the waste canisters has not been modelled since it is assumed to be of less importance than the bentonite filled tunnels. The metallic canisters are likely to produce a weak but slowly decaying field. The time constant of such a field will probably be significantly larger than the cycle period of a TEM system. This will make the field difficult to measure.

The modelling program has a limited precision, especially at late delay times, which can be observed as a lack of smoothness in the decay curves in Figure 3-17 and the too quick decay rate at late times.

The resistivity of the surrounding bedrock will be dependent upon the salinity of the pore-water. The present day situation might change due to e.g. glaciation and sea-water level variations.

3.6 Induced polarization and resistivity

Modelling of the response of the repository to a resistivity and induced polarisation (IP) survey has been carried out using the program ModelVision ver.10, © Encom Technology and DCIP3D from UBC, University of British Columbia.

From the parameter compilation in Section 2.2.5 and 3.1, the bedrock resistivity is set either to 3,000 ohmm (brackish water) or 14,482 ohmm (no saline water) and the IP to 0.25 in both cases. In the modelling, a 10 m thick surface layer of moraine or similar material is presumed, at a resistivity of 500 ohmm and an IP of 0. At depth, from 800–1,500 m, a saline groundwater is presumed in some models, at a resistivity of 800 ohmm and an IP of 0.

The transport tunnels are filled with Milos bentonite and hence have been assigned a resistivity of 3 ohmm and an IP of 1.

In the deposition tunnels, the Milos bentonite has a low resistivity, 3 ohmm, and calculating the effective resistivity in a sub-volume cross-section perpendicular to the tunnels give a resistivity of ca. 30 ohmm, which is used in the model. The IP-effect is set to 0.75 since the bentonite is assumed to give a rather large influence in the deposition tunnel sub-volumes as a whole.

The average resistivity and IP parameters for the canister sub-volumes are difficult to decide upon. The average effective resistivity perpendicular to the vertical deposition holes, that is horizontally, is calculated to 320 ohmm. The weighted average resistivity based on the respective volumes is determined to ca. 2,900 ohmm. Hence, the average resistivity is estimated to 1,000 ohmm based on a geometric mean of the two situations. In a similar way IP is set to 0.37 as an average for the canister sub-volumes.

3.6.1 Response from the different alternatives

Figures 3-20 to 3-24 present vertical pseudo sections of modelling responses from different survey configurations and with the two resistivity models used, Section 2.2.5. The profile is directed in south-north, across the repository and along co-ordinate 1631600 East, Figure 2-4. From the modelling it is clear that an anomaly is obtained from the repository. However, the signal is very small compared to background and the shape of the anomaly is more or less flat lying and not easy to identify. The induced polarisation gives the clearest anomaly in pole-dipole and dipole-dipole configuration, Figures 3-20b and 3-22b, and the model with saline ground water at depth. The

IP-response from the model based on no saline groundwater at depth gives a somewhat different anomaly pattern, Figure 3-24b. The resistivity anomalies from the models with saline groundwater at depth, in general, show a successive decrease in resistivity towards depth, from which it is very difficult to identify any divergent patterns.

The gradient configuration, Figure 3-25, shows a clear decrease in resistivity with ca. 200 ohmm in the central part of the profile, depending on if the repository is modelled or not. The IP response at the same time increases from 0.23 to 0.26.

The gradient survey used here can easily be carried out today; the technique is in general use. The dipole-dipole and pole-dipole configurations are more extreme, commonly only 8 dipoles are used in today's equipment. However, the usage of deep resistivity and IP surveys are developing fast so these configurations and surveys can be in general use in a near future.

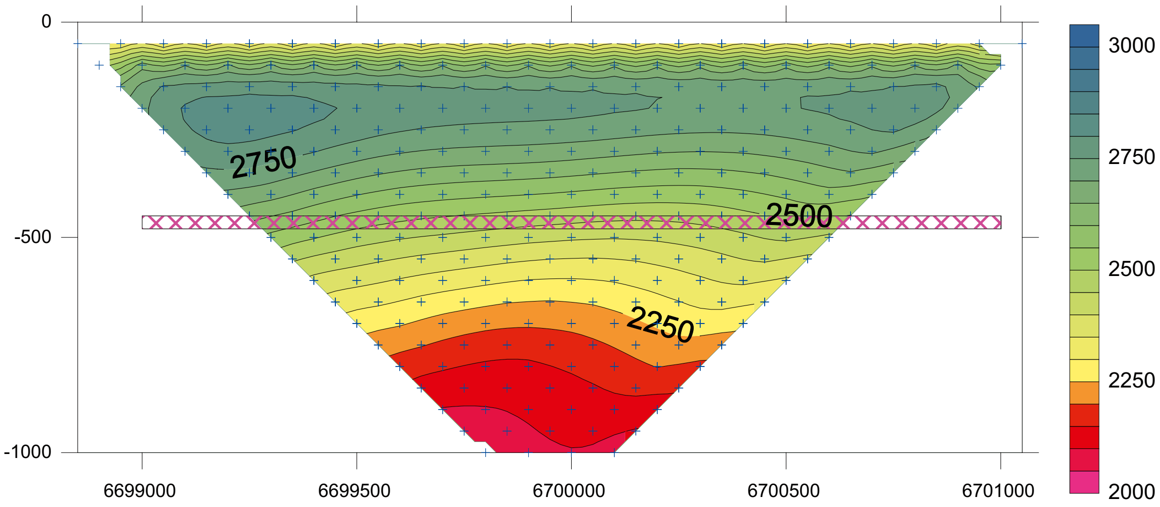

Figure 3-20a. The resistivity response from the repository [ohmm] calculated as a pseudo-section along line 1631600 East. Pole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.

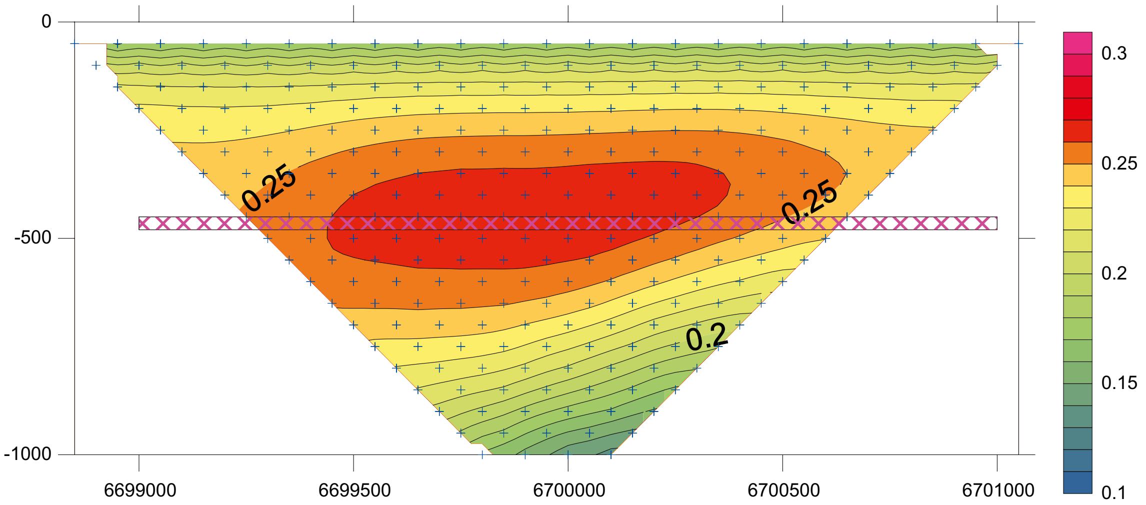

Figure 3-20b. The IP response from the repository [unit less] calculated as a pseudo-section along line 1631600 East. Pole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth, shown by a magenta-hatched rectangle.

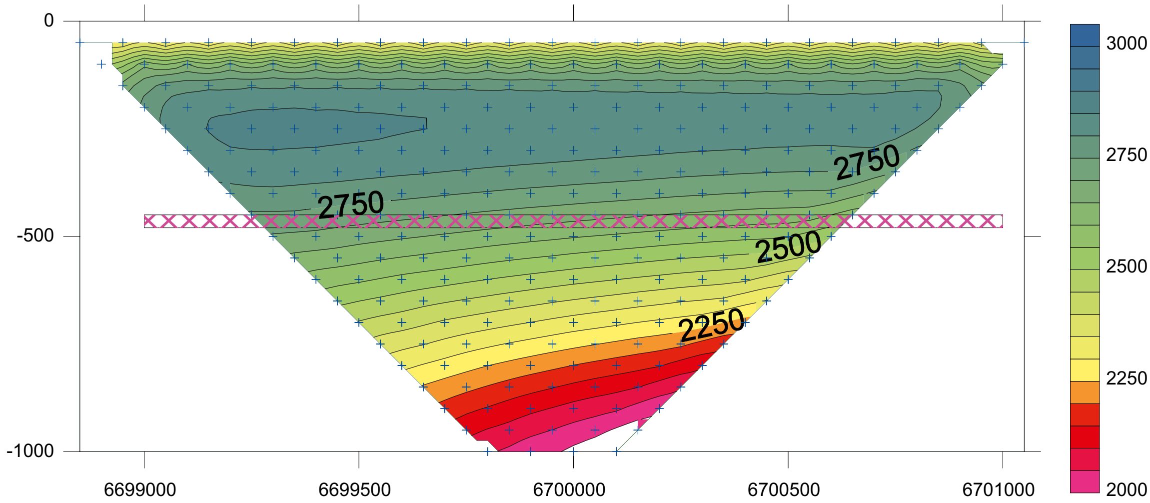

Figure 3-21a. *The resistivity response* ***without the repository*** *[ohmm] calculated as a pseudo-section along line 1631600 East. Pole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.*

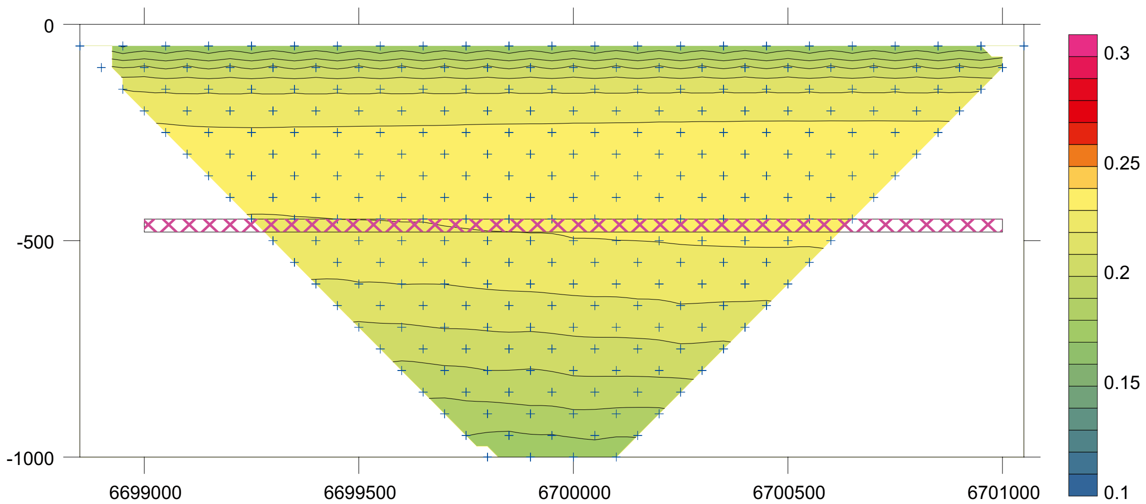

Figure 3-21b. *The IP response* ***without the repository*** *[unit less] calculated as a pseudo-section along line 1631600 East. Pole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.*

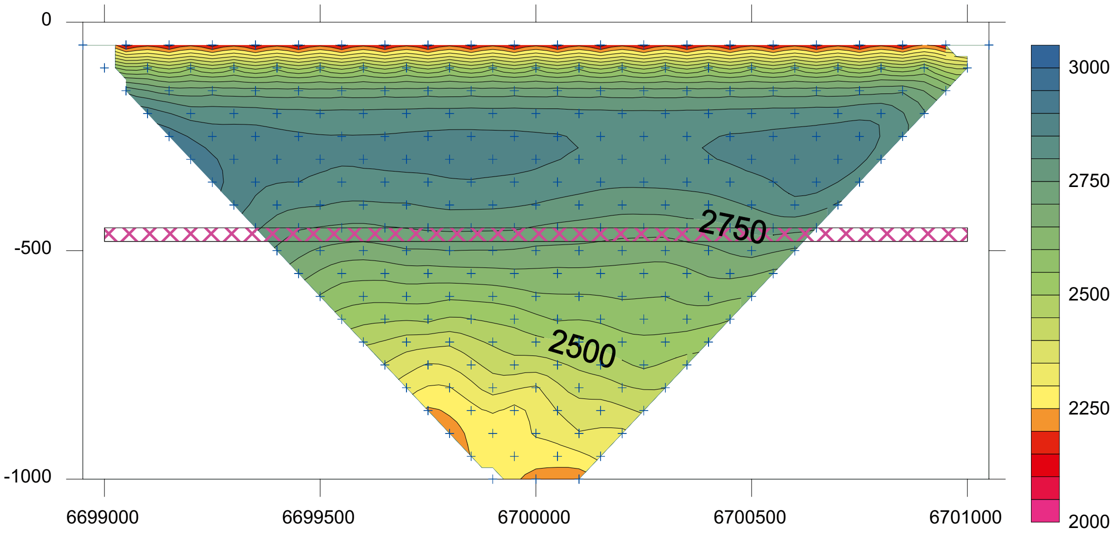

Figure 3-22a. *The resistivity response from the repository [ohmm] calculated as a pseudo-section along line 1631600 East. Dipole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.*

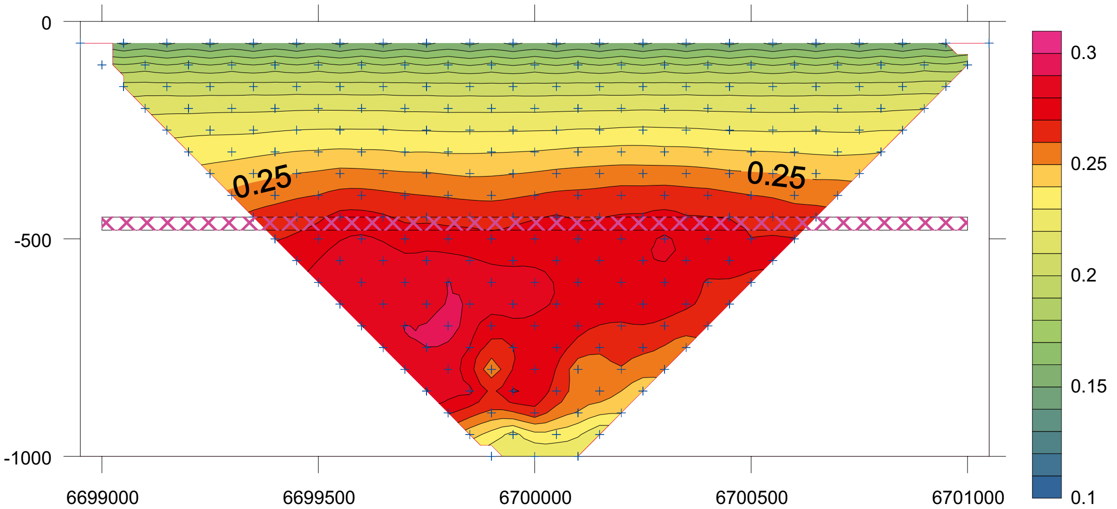

Figure 3-22b. *The IP response from the repository [unit less] calculated as a pseudo-section along line 1631600 East. Dipole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.*

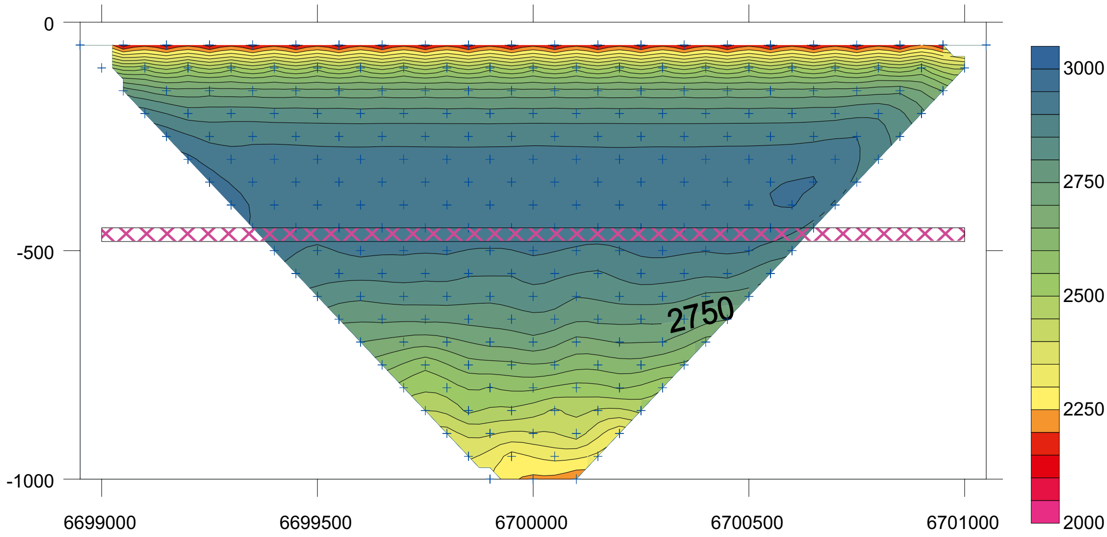

Figure 3-23a. *The resistivity response without the repository [ohmm] calculated as a pseudo-section along line 1631600 East. Dipole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.*

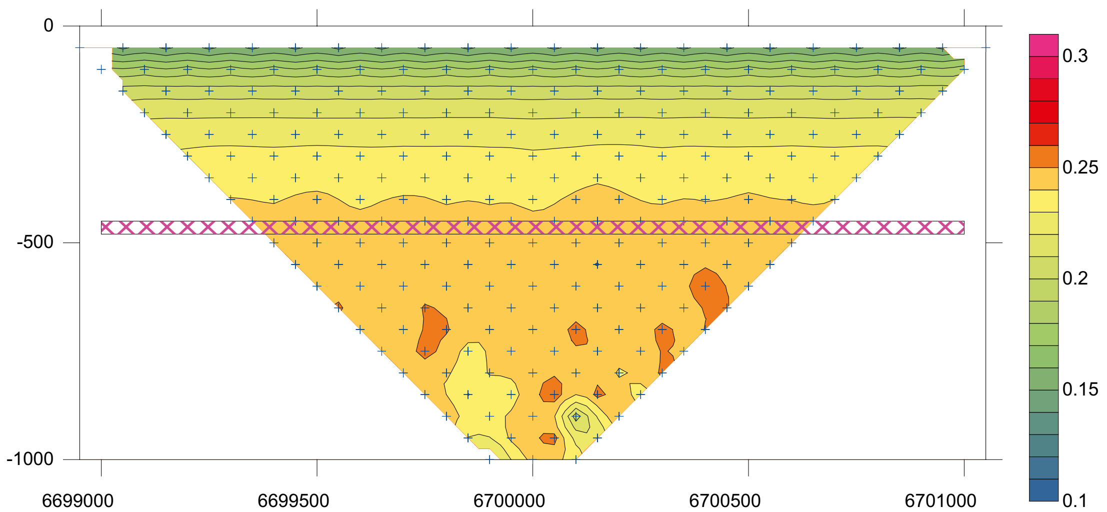

Figure 3-23b. *The IP response without the repository [unit less] calculated as a pseudo-section along line 1631600 East. Dipole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model includes saline groundwater at depth and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.*

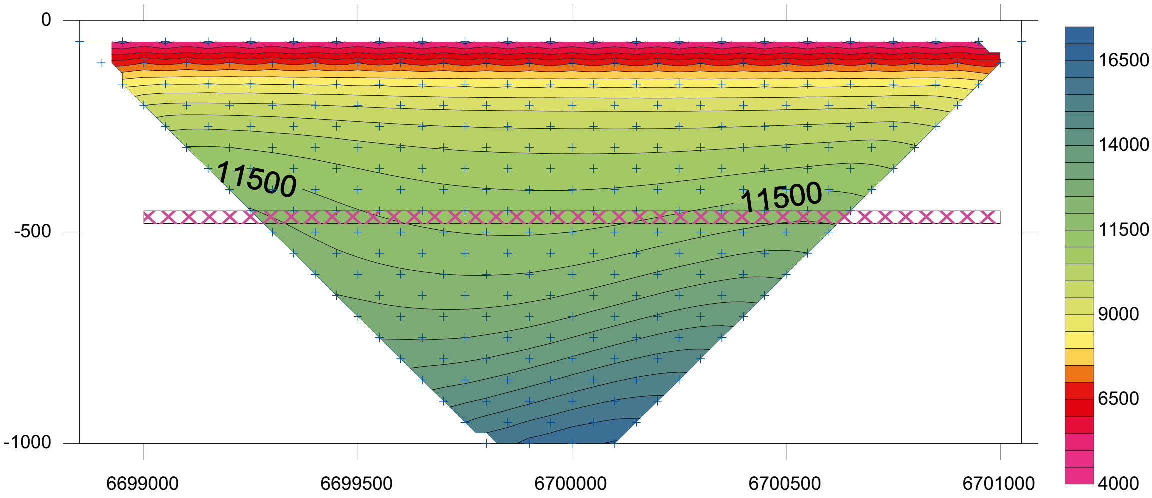

__Figure 3-24a.__ The resistivity response from the repository [ohmm] calculated as a pseudo-section along line 1631600 East. Pole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model does not include saline groundwater at depth and includes higher bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.

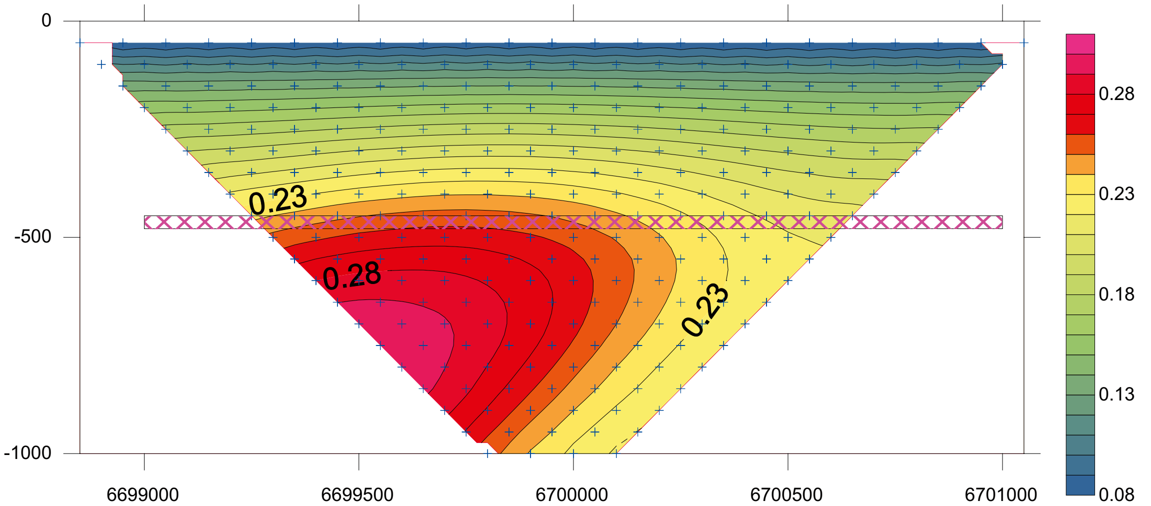

__Figure 3-24b.__ The IP response from the repository [unit less] calculated as a pseudo-section along line 1631600 East. Pole-dipole configuration with dipole length a=100 m and number of dipoles n=20. Model does not include salt groundwater at depth and includes higher bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth.

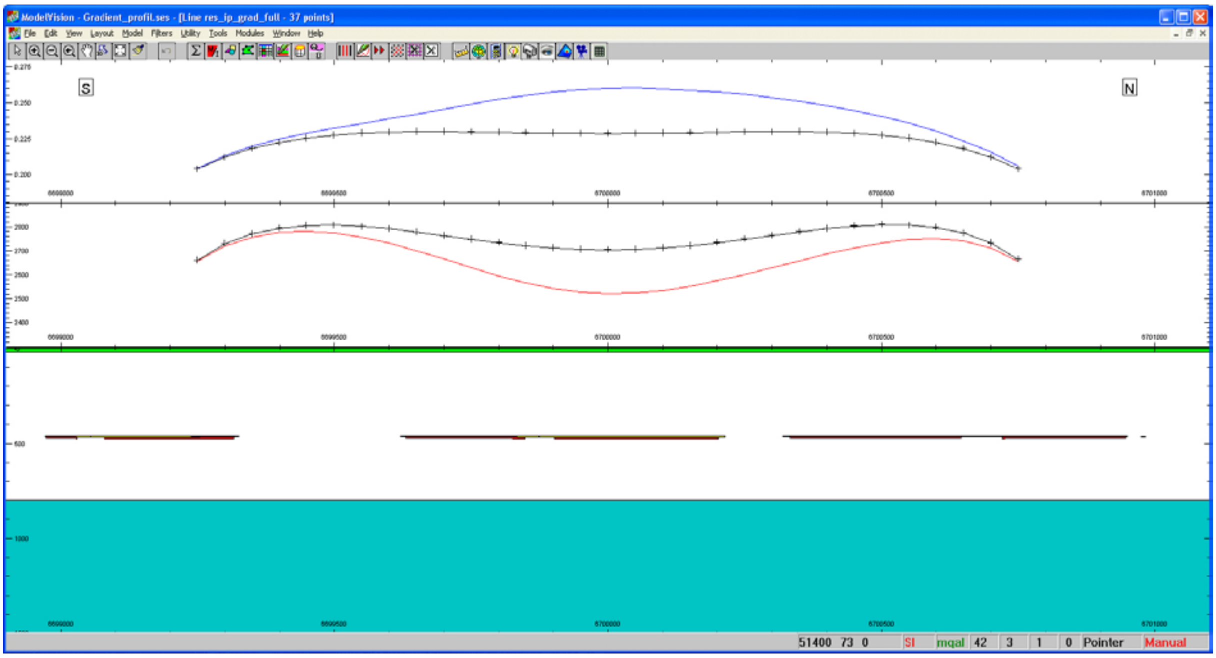

Figure 3-25. The resistivity (lower section) and IP (upper section) response from the repository calculated from a gradient configuration along line 1631600 East. The black lines show the response without the repository and the resistivity and IP responses with the repository is shown by the red and blue curve, respectively. Model includes saline groundwater at depth (cyan) and lower bedrock resistivity. Repository located between 6699000–6701000 and 450–480 m at depth. A layer of moraine is included at surface in the model (green).

3.6.2 Signal/noise

/Thunehed et al. 2004/ report results from profile measurements with induced polarisation and resistivity over lineaments inferred to represent deformed bedrock in the Oskarshamn region. The profile LSM000279 is used to compare the anomaly distribution and amplitudes of a typical geological situation that could be expected also from the Forsmark area, Figures 3-26a and 3-26b. When relating the responses from the theoretical calculations from the repository with the real data from profile LSM000279, with its irregular anomaly patterns and quite high amplitudes, it becomes probable that the response from the repository will be obscured as soon as other disturbances than the repository are involved.

3.6.3 Uncertainties

The IP response in general shows a stronger response below the repository and this is especially accentuated in Figures 3-22b and 3-24b. The cause of this is uncertain.

The resistivity and IP parameters used for the repository sub-volumes are uncertain and probably over-estimated.

How well the voxel model represents the actual repository geometry and layout is uncertain and difficult to control.

The inversion programme shows instabilities in dipoles calculated close to the boundary of the finest voxel mesh.

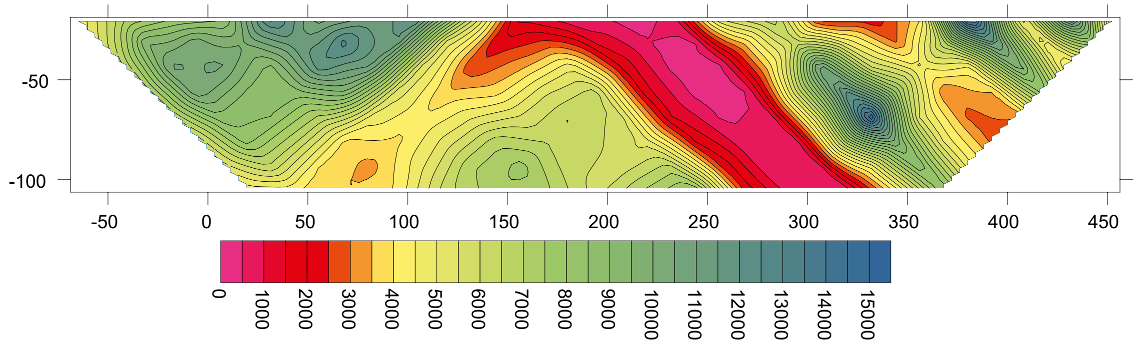

Figure 3-26a. *The resistivity response [ohmm] from a ground survey profile at Simpevarp.*

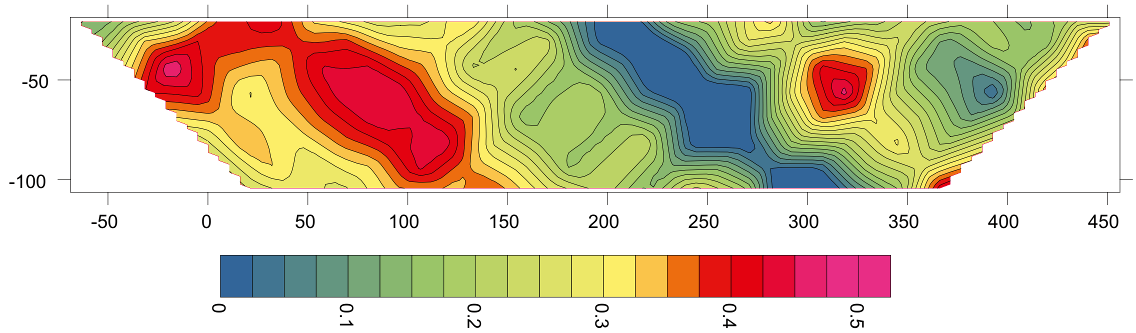

Figure 3-26b. *The IP response [unit less] from a ground survey profile at Simpevarp.*

4 Analysis, discussion and conclusions

The main objective of this investigation was to test if there could be a measurable response at the ground surface from a radioactive waste repository buried at a depth around 500 m below the surface. The geophysical methods to be tested include: magnetics, gravity, transient EM (TEM), galvanic resistivity, induced polarization (IP) and reflection seismics.

The gravity response from the model repository shows a maximum amplitude of –0.009 mGal, which is close to the noise level of a modern gravity meter instrument. In comparison, a minor iron-oxide mineralization at shallow depth would typically give rise to a gravity anomaly in the order of 0.5–1.0 mgal. With today's state of the art instruments and modelling tools it is difficult to perform reliable modelling of natural anomalies smaller than c. 0.05–0.1 mgal in environments with "normal" geological noise. In this perspective and with reference to the present gravity anomaly distribution at Forsmark, the gravity response of a repository is negligible. A similar result has been reached also in the magnetic modelling work. The magnetic anomaly response from the model repository is in the range –0.01 nT to 0.06 nT. This is within the noise level of a modern magnetometer, and compared to the natural variation in the magnetic anomaly field of around 1,200 nT at Forsmark, the contribution from the repository can be considered as negligible. One important uncertainty in the gravity and magnetic modelling work is the simplification of the model repository into sub-volumes and the simplified magnetic field from the canisters that result in a generalization of the anomaly pattern. However, taking into account the decrease in the magnetic and gravitational field strengths with distance from the source this effect is most likely insignificant in data from surface based measurements.

In the transient electromagnetic (TEM) modelling the model repository generates a secondary field for the vertical component that is approximately twice as high compared to the model in natural ground without the repository. The repository would thus, in principle, be detectable with a TEM-system. However, in the model, the rock surrounding the repository is set to have a constant resistivity down to 900 m depth, whereas natural resistivity variations in the bedrock may be of at least one order of magnitude. Previous TEM soundings made by GeoVista in the Forsmark area show variations in signal magnitude significantly larger than the effect of the model repository. Therefore, it is hardly likely that a minor, although measurable, change in apparent resistivity as expected from the repository would be experienced as a possible mineralization at depth. The main uncertainty in the TEM-modelling is the high degree of simplification of the model. A simplified model with adjusted resistivity had to be used. However, we also tested a model with significantly lower than expected effective resistivity, and still the response of the repository was not very strong.

The modelled response of the repository for IP and resistivity gives significant anomalies. However, the signal is very small compared to background and the anomaly from the repository is difficult to identify even without natural geological disturbances. In the induced polarisation modelling significant anomalies occur when using both pole-dipole and dipole-dipole configuration. With saline groundwater at depth, the resistivity anomalies in general show a successive decrease in resistivity towards depth, from which it is very difficult to identify any divergent patterns caused by the repository. With a gradient configuration there is a significant decrease in resistivity and also increased IP effect caused by the repository. However, when relating the responses from the theoretical calculations from the repository with real survey data from Simpevarp, that represents a typical geological situation comparable with the one at Forsmark, it becomes probable that the response from the repository will be obscured by geological noise. Just as for the TEM-modelling uncertainties in the IP and resistivity model responses are mainly related to the model simplification.

For the reflection seismics two models were tested, one without a repository and one with the deposition tunnels of the repository included. There is a clear seismic response from the repository in the synthetic sections. This is due to the large contrast in velocities (both P-wave and S-wave) of the bentonite compared to the surrounding granitic rock used in the modelling and it is likely that the repository would be detected in real data.

/Parasnis 1982/ carried out an investigation with a similar objective to what is reported here. At the time of his study computerized modelling tools were very limited and most of /Parasnis 1982/ work is based on theoretical calculations and analogue models constructed in the laboratory. The results from this study are mainly in accordance with the conclusions from the previous study by /Parasnis 1982/. However, the methods ground penetrating radar (GPR), VLF, slingram, magnetotelluric sounding (MTS) and geothermal measurements were investigated by /Parasnis 1982/ and they are not included in the present study while TEM was not included by Parasnis. Both studies include magnetics, gravity, resistivity, IP and reflection seismics.

The conclusion by /Parasnis 1982/ for those methods that were not included in this study was that a repository might be detected by radar, and for geothermal measurements it would probably give an increased geothermal gradient detectable even in shallow drill holes. However, borehole radar measurements conducted in Forsmark have yielded ranges of less than 100 m, see e.g. /Gustafsson and Gustafsson 2004/. Hence, it is not likely that radar measurements from the ground surface would detect a repository at 500 m depth. The thermal response of the repository has been calculated in recently performed research projects, and the maximum increase in temperature at 100 m depth is estimated at 4 degrees C after approximately 1,000 years, /Hökmark et al. 2010/. This would be detectable in thermal measurements. The result for MTS and slingram was not conclusive depending on the theoretical complexity of the calculations, while the result for the VLF method clearly showed that the repository could not be detected.

In the study by /Parasnis 1982/ seismic methods were not discussed in any detail but he did not exclude the possibility for a detectable response from a repository. In the study presented in this report it is clearly shown that the repository will give a distinct signal for reflection seismics that is similar in magnitude to a larger fracture zone or a discontinuity caused by the contact between rock units of clearly different composition.

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SKBdoc id, version	Title	Issuer, year
1217234 ver 1.0	Beräkning av kapselkomponenters vikt	SKB, 2009