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An overview of a possible approach to calculate rock movements due to earthquakes at Finnish nuclear waste repository sites

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AN OVERVIEW OF A POSSIBLE APPROACH TO CALCULATE ROCK MOVEMENTS DUE TO EARTHQUAKES AT FINNISH NUCLEAR WASTE REPOSITORY SITES

Tiivistelmä - Abstract

This report outlines a possible approach to estimating rock movements due to earthquakes that may diminish canister safety. The method is based upon an approach developed for studying similar problems in Sweden at three generic Swedish sites. In the first part of the report, the problem of rock movements during earthquakes is described. The second section of the report outlines the approach used to estimate rock movements in Sweden, and discusses how the approach could be adapted to evaluating movements at Finnish repositories. This section also discusses data needs and potential problems in applying the approach in Finland. The next section presents some simple earthquake calculations for the four Finnish sites. These simulations use the discrete fracture network model geometric parameters developed by VTT for use in hydrological calculations. The calculations are not meant for performance assessment purposes for reasons discussed in the report, but are designed to show (1) the importance of fracture size, intensity and orientation on induced displacement magnitudes; (2) the need for additional studies with regards to fracture size and intensity; and (3) the need to resolve issues regarding the role of post-glacial faulting, glacial rebound and tectonic processes in present-day and future earthquakes.

Avainsanat - Keywords
rock movements, earthquakes, modelling, disposal of nuclear waste

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ERÄS MENETELMÄ MAANJÄRISTYKSISTÄ AIHEUTUVIEN KALLIOSIIRROSTEN LASKEMISEKSI KÄYTETYN YDINPOLTTOAINEEN LOPPUSIJOITUKSEN TUTKIMUSPAIKOILLA SUOMESSA

Tiivistelmä - Abstract

Tässä raportissa kuvataan erästä mahdollista menetelmää sellaisten maanjäristyksistä aiheutuvien kalliosiirrosten arvioimiseksi, jotka voisivat vahingoittaa loppusijoituskapselia. Menetelmä perustuu samaan lähestymistapaan, joka on kehitetty kalliosiirrosten arvioimiseksi kolmella esimerkkipaikalla Ruotsissa. Raportin johdannossa kuvataan maanjäristyksiin liittyvien kalliosiirrosten problematiikka. Työn toisessa luvussa kuvataan Ruotsin paikkojen kalliosiirrosten arvioimiseen käytetty lähestymistapa, ja luvussa tarkastellaan myös lähestymistavan käyttämistä siirrosten arvioimiseksi tutkimusalueiden kallioperässä Suomessa. Toisessa luvussa tarkastellaan edelleen tarvittavia lähtötietoja ja mahdollisia menetelmän käyttöön liittyviä ongelmia sovellettaessa sitä tutkimuspaikoille Suomessa. Luvussa kolme esitetään joitakin yksinkertaisia maanjäristysten etäisyyden ja voimakkuuden vaikutusten tarkastelemiseksi tehtyjä laskuja neljälle tutkimuspaikalle Suomessa. Näissä simulaatioissa on käytetty samoja rakoverkkomallin parametreja, joita on käytetty VTT:ssa suoritetuissa pohjaveden virtauslaskuissa. Maanjäristysten vaikutuksesta tapahtuvien kalliosiirroslaskujen tulokset eivät ole tarkoitettu käytettäväksi turvallisuusanalyyseja varten raportissa esitettyjen syiden vuoksi. Laskujen tarkoituksena on ollut osoittaa (1) rakokoon sekä rakojen määrän ja asennon merkitys indusoitujen siirrosten suuruudelle; (2) lisätutkimusten ja selvitysten tarve koskien rakojen kokoa ja määrää; ja (3) tarve ratkaista jääkauden sulamisvaiheeseen liittyvät järistys- ja siirroskysymykset sekä jääkauden jälkeisen maankohoamisen ja tektonisten prosessien kysymykset koskien nykyisiä ja tulevia maanjäristyksiä.

Avainsanat - Keywords
kalliosiirros, maanjäristys, mallinnus, ydinjätteiden loppusijoitus

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1 INTRODUCTION

1.1 Conceptual scenario

Rock movements due to earthquakes may cause fractures intersecting canister holes to slip. This slippage may be primary when the earthquake occurs on the fracture intersecting the canister hole, or secondary when the slippage is induced by an earthquake taking place on a fault at some distance from the fracture intersecting the canister hole (Figure 1-1). While individual earthquakes might not produce slippage of sufficient magnitude to damage a canister or the buffer around it, repeated earthquakes over tens of thousands of years might produce sufficient net cumulative slip to reduce canister integrity.

Present-day levels of seismicity in Fennoscandia are relatively low. However, there is evidence that large earthquakes may have occurred several thousand years ago due to de-glaciation (Saari 1992, Lukashov 1995). Based upon the dimensions of the traces along which these earthquakes may have taken place, the magnitudes could have been greater than 7 (Muir-Wood 1989). Thus earthquakes, whether purely tectonic in origin or related to rebound and de-glaciation, could impact future repository safety, and need to be considered as a possible future scenario.

1.2 Previous studies

Numerical calculations of the slippage that might occur on fractures intersecting canister holes due to earthquakes have not been carried out for proposed repository sites in Finland, although numerous studies have been carried out to quantify the geology, seismotectonics and earthquake hazard in Finland and surrounding countries. There have been recent efforts within the Swedish program to develop a methodology (La Pointe et al. 1997, 1998) to estimate earthquake impact for the purpose of performance assessment. The approach uses a conservative numerical simulation approach to model earthquake effects. It is possible that this approach could be adapted to assess the performance of the four sites in Finland. Section 2 describes the methodology as it has been applied to the three generic repository sites in Sweden. Also discussed is the type of data that is necessary to do the modeling, its availability in Finland, and the strengths and weaknesses of the approach for Finnish sites. Section 3 illustrates how the method could be applied to Finnish sites through a series of simple earthquake distance-magnitude simulations. These illustrative calculations are based on existing discrete fracture network models of the four candidate sites, but do not incorporate any other site-specific geological data or earthquake magnitude-frequency recurrence statistics. There purpose is to show the steps involved in making induced-slip calculations, and also to point out what types of additional data would be required for site-specific calculations that could be used in a performance assessment calculation.

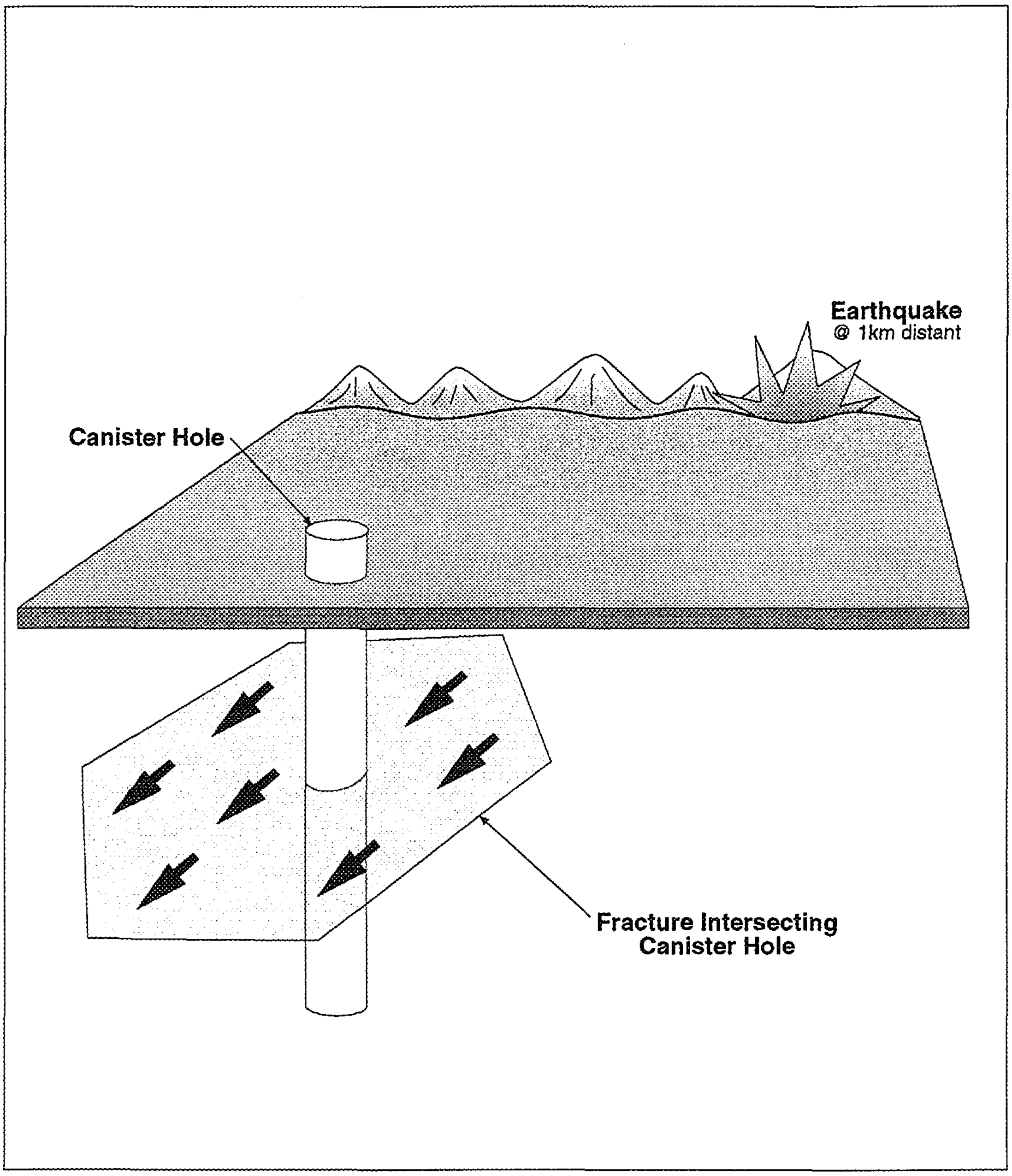


Figure 1-1. Fracture slippage due to an earthquake.

2 APPLICATION OF SWEDISH METHODOLOGY TO FINLAND

2.1 Description of methodology

The methodology to estimate the impact of repeated earthquakes on fractures intersecting canister holes has been elaborated by La Pointe et al. (1997, 1998). Figure 2-1 illustrates the overall approach, which consists of four stages:

Stage 1 – Analysis of fracture trace data

Stage 2 – Discrete Fracture Network (DFN) model generation

Stage 3 – Determination and specification of seismic boundary conditions

Stage 4 – Numerical earthquake simulation

The strategy of the approach is to realistically model both the structural geology of a site and the future seismic evolution of the region surrounding it. Stage 1 and 2 consist of the analysis of the site-specific geological data and the generation of a three-dimensional representation of the fracturing in the rock mass. The numerical representation of the fracturing is through a Discrete Fracture Network (DFN) model, such as that shown in Figure 2-2. Each polygon in the model represents a fracture. Fracture properties such as orientation, size, intensity and mechanical properties are assigned to each fracture. This assignment can be based on statistics derived from outcrop or borehole data; conditioned to mappable geological parameters like curvature, proximity to shear zones and lithology; or in the case of large faults detected through drilling or geophysics, deterministically placed in the model. In the model shown in the Figure, fracture orientations are related to bedding curvature, while fracture intensity varies according to lithology. A large fault mapped from the surface displaces the fractured layer of rock. Unless the model is entirely comprised of deterministic features, there will be a stochastic component of the numerical model that allows for uncertainty regarding the fracturing to be propagated through to the final slip calculations. A description of the DFN model used for the Swedish studies can be found in La Pointe et al. (1997).

Stage 3 requires estimation of future earthquake magnitudes and recurrence rates, which are used in the final numerical modeling. This information is used both directly and indirectly in the modeling process. First, it is used directly to specify the number and magnitude of all of the earthquakes that are likely to occur during the period of repository performance. Additional earthquake-related information is needed for the modeling, however. The numerical model represents the fault on which the earthquake takes place as a polygon, typically as a rectangle (Figure 2-3). The fault's surface rupture length and its down-dip width define the size of this rectangle. For a vertical fault, the down-dip width would equal the vertical dimension of the fault. The earthquake itself is modeled as an instantaneous elastic dislocation or displacement occurring over the polygon. Studies have shown (for example, Wells and Coppersmith 1994) that the magnitude of an earthquake is strongly correlated to the surface rupture length, the rupture width (or depth), and the fault

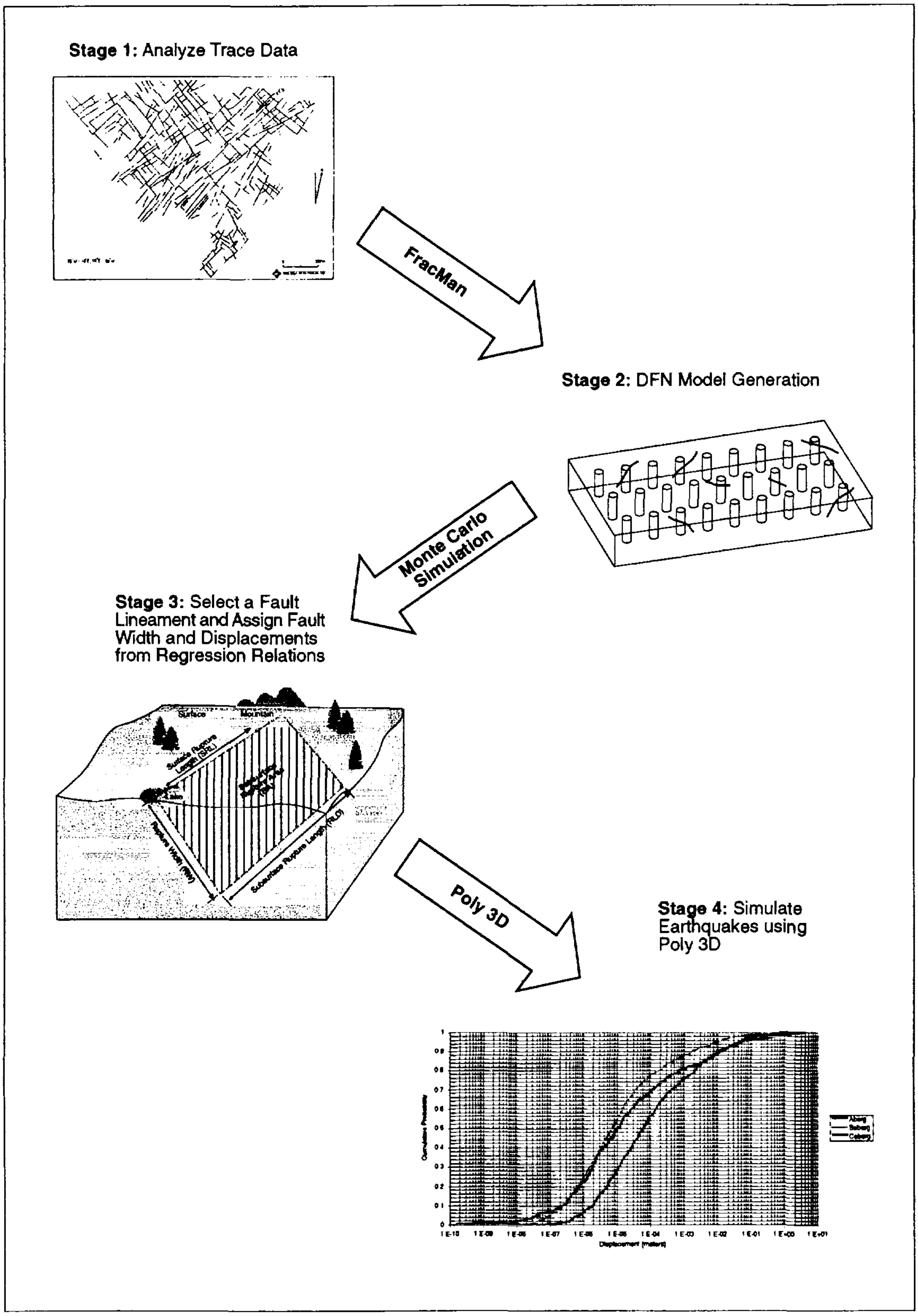


Figure 2-1. Four-stage process for estimating earthquake-induced displacements.

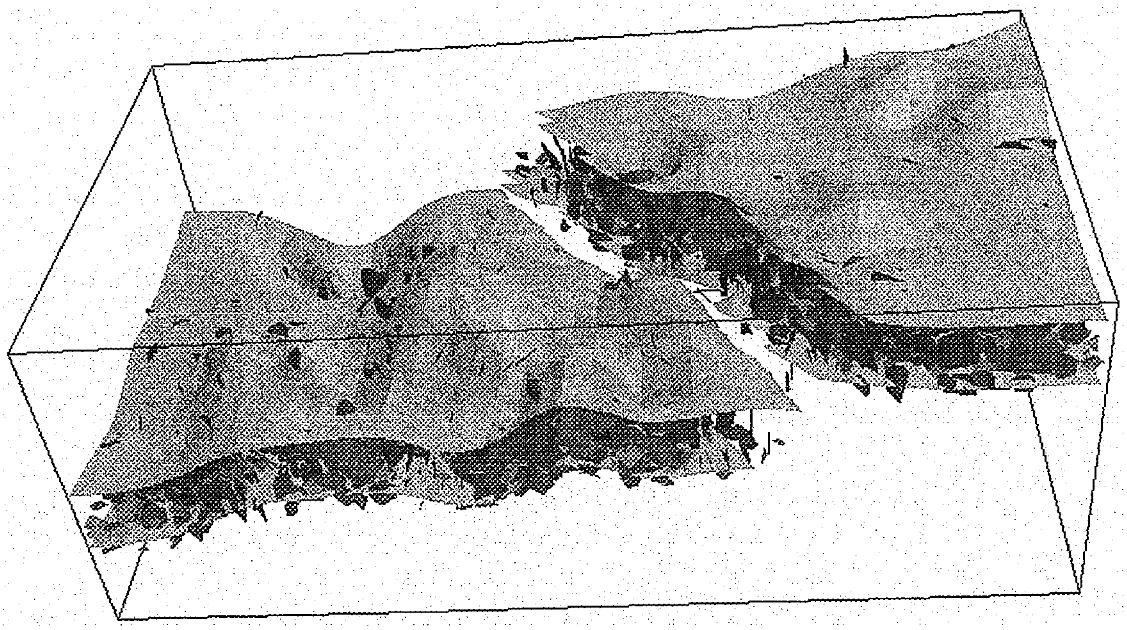


Figure 2-2. Example of a discrete fracture network (DFN) model of jointing and faulting in a rock mass.

displacement. Thus, it is possible to assign (with some uncertainty) the minimum length and width of a fault that would be large enough to produce an earthquake of the specified magnitude, and also to assign an instantaneous elastic displacement to that fault. Earthquake location is also important. The modeling approach applied to the Swedish sites assumes that future earthquakes are likely to occur along existing faults, which are expressed as lineaments. Locations of future earthquakes are determined by searching for a lineament that has a surface trace length long enough to have been capable of having the earthquake of the specified magnitude. Additional geological constraints can be imposed on earthquake locations if warranted if the pattern of seismicity is not uniform within the region under consideration.

The final stage, Stage 4, consists of the numerical earthquake simulations. It is in this stage that the site-specific structural data, represented as DFN models, the proposed canister layouts, and the seismic information are all combined. The waste canisters are represented as cylinders within the DFN model, and the intersections between all canisters and the fractures in the DFN model are computed. Next, a series of numerical simulations are carried out on this DFN model to simulate the impact of future earthquakes. For larger earthquakes, a lineament is found as described in Stage 3 that becomes the site for the earthquake. For smaller earthquakes, the location is chosen at random, but the surface rupture length and width of the fault are still chosen based upon the correlation between magnitude and rupture geometry, as is the case for the larger magnitude earthquakes. A three-dimensional, linearly elastic fracture mechanics code called POLY3D (Thomas 1993) is used to calculate the secondary displacements induced on the fractures intersecting the canister holes by the earthquake. This calculation is repeated for all earthquakes forecast for the period of performance. The net cumulative displacement is tracked to determine if

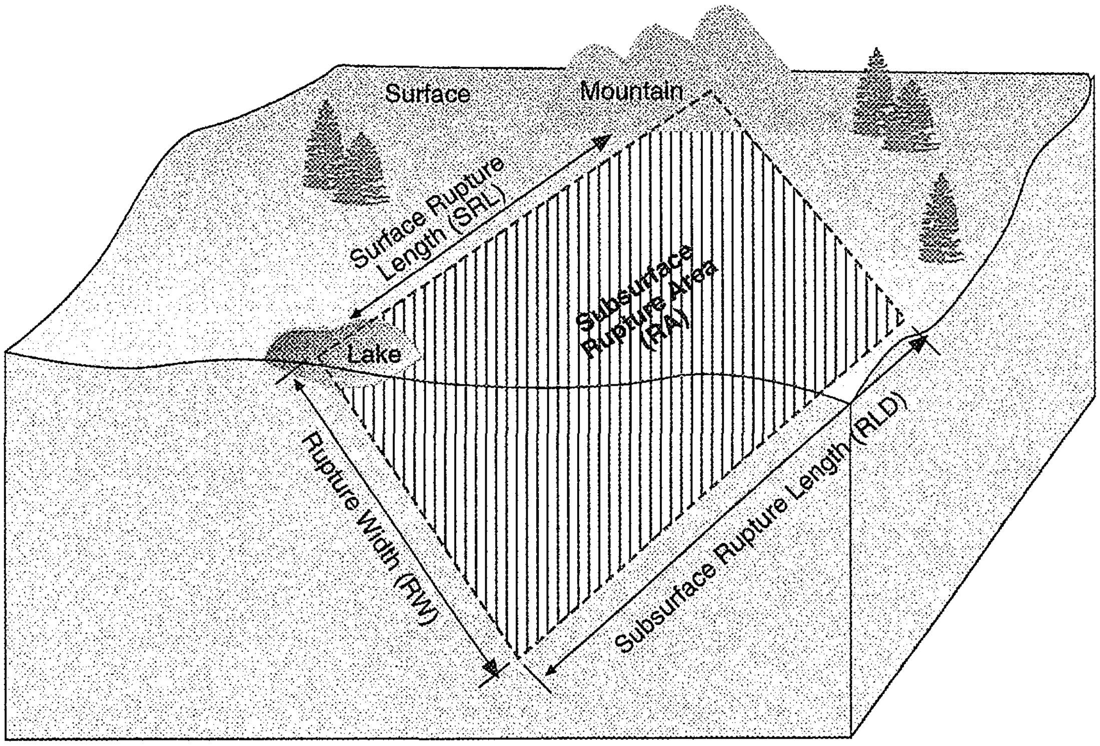


Figure 2-3. POLY3D Fracture Model.

at any time it exceeds a specified displacement threshold. For the Swedish studies, the threshold used is 0.1 m of displacement.

This approach simplifies the dynamical-mechanical processes that actually occur in the rock during an earthquake (Figure 2-4). This simplification has the dual benefit of reducing the numerical effort involved, and also producing conservative results.

First of all, the rock is represented as a linearly elastic material. This means that all of the earthquake energy goes into elastic deformation of the secondary fractures. None of the energy is dissipated in ductile or plastic rock deformation. This tends to maximize the displacement induced on fractures intersecting the canisters, and is thus conservative.

Actual earthquakes do not apply an instantaneous load on the rock; rather, they apply a cyclical load over a period of seconds. Rock and rock fractures tend to be weaker under cyclic loading as compared to static loading, allowing them to deform or displace under lower peak stress levels. In terms of fracture deformation, the weakening comes about through the degradation of the fracture surface, reducing friction and/or cohesion. The dynamic, cyclic loading has been simplified by treating the fractures as frictionless and cohesionless in the numerical modeling, and is thus conservative.

All estimates of induced fracture displacements are made at the fracture midpoint where displacements are maximized, and is thus conservative.

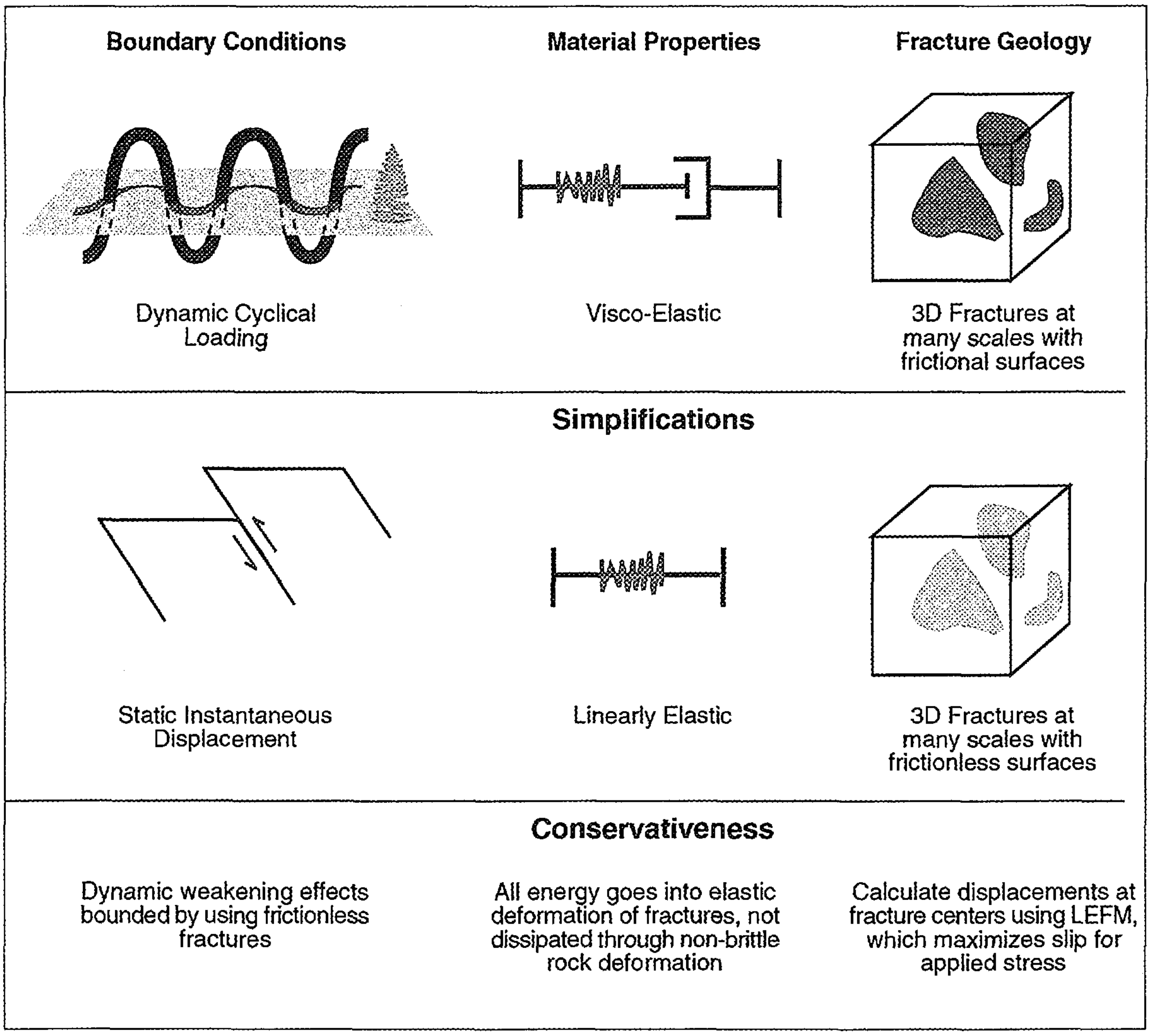


***Figure 2-4**. Simplifications used in the numerical simulation of earthquakes.*

In a linearly elastic material, the displacement induced on a fracture by a dislocation on another fracture does not depend upon any other fractures. Therefore it is not necessary to represent all of the fractures between the fault on which the earthquake occurs and the fracture intersecting the canister in order to take into account the dissipation of earthquake energy along other fractures. The deformation produced on each fracture is as if each fracture were the only one within an elastic material. This situation tends to maximize induced displacement.

Another benefit of using a linear elastic model is that the induced displacements are a linear function of the energy produced by the dislocation. This energy is related to the product of the shear modulus of the rock hosting the fault, the rupture area of the fault, and the average displacement over the rupture area of the fault. Since the earthquake magnitude is a function of this energy release as well, the net induced displacements will be the same whether one single large earthquake occurred on a particular fault, or several smaller earthquakes occurred such that their total released energy was the same as the single earthquake. The only difference is in the timing of when the displacements occur. This makes it less difficult to model post-glacial faulting, as described in Section 2.3.

In summary, the modeling approach developed for evaluating the safety of the three generic Swedish repositories uses a realistic three-dimensional numerical representation of fracturing, integrated with the proposed canister layouts and any model for the recurrence rates and spatial models for future earthquakes. The numerical modeling of the earthquakes represents a conservative simplification of the more complex dynamical processes that occur in the rock during an earthquake. The results are stochastic and allow for the incorporation of uncertainties regarding the fracture geometry, future earthquake patterns, and the relation between earthquake magnitudes and rupture geometry.

The type of information that can be produced is quite varied, depending upon how the performance assessment calculation uses the information. For the studies reported in La Pointe et al. (1998), the measure of repository performance is the probability that a fracture intersecting a canister would experience net cumulative displacements exceeding 0.1 m at any time over the next 100,000 years.

By carrying out the numerical earthquake simulations for different realizations of the DFN models and for the order and location of earthquakes over the 100,000-year time period, it was possible to produce a distribution of results. In many of the realizations, no canisters failed, while in others, one or more canisters failed. These outcomes were compiled into probabilities associated with the percentage of canisters that failed. The median failure percentage was zero since 70% to 90% of the simulations had no displacements greater than 0.1 m. The mean canister failure percentages were on the order of 0.03%. The major differences between the probabilities appears to have been a function of the b value for the earthquake recurrence rate used, and the mean fracture size and intensity. As the b value increases, the relative proportion of large to small earthquakes increases. Large earthquakes, typically those greater than magnitude 5, have the greatest negative impact on the canisters. Also, when fracture intensity is greater, it is more probable that canisters will intersect fractures. The more canisters there are that intersect fractures, the more canisters there are that could potentially fail. In addition, fracture size plays a role. The larger the fracture, the greater the maximum induced slip can be. Thus, sites that have a higher fracture intensity, larger fractures and are affected by earthquakes whose recurrence rate is characterized by a low b value should perform less optimally than sites with the opposite characteristics, all other parameters being equal.

These results indicate the importance of correctly estimating fracture size and intensity, as well as the earthquake parameters. The next section discusses that availability and quality of data for this type of modeling at the four Finnish sites.

2.2 Data availability & feasibility

The approach described in Section 2.1 integrates several types of data:

- detailed, site-specific structural geology for creation of discrete fracture network models;
- regional lineament maps to identify faults on which future earthquakes may occur;
- present-day seismic hazard parameters for extrapolating earthquake recurrence rates into the future;
- the site-specific repository geometry; and
- scenarios for the tectonic/glacial evolution of the sites over the period of performance.

The uncertainty in the estimates of canister failure depends upon the uncertainties in the data. Of the items listed above, the repository geometry is specified, not estimated from a data sample. The remaining four items have much greater uncertainty. Each will be discussed in turn.

A substantial amount of work has been done on the structural geology at the four candidate sites. Analysis of borehole and surface fracture data has enabled VTT to produce DFN models for all four sites. The current DFN models for these sites were designed for flow and transport calculations at a particular scale. The current flow and transport modeling approach requires that blocks at around the 40 m scale need to be explicitly represented as DFN models. At this scale, medium and large fractures will be rare. However, for earthquake simulations, all scales of fracture data are required. In particular, the larger fractures are very important, since the Swedish work has shown how the large fractures have the greatest potential for large displacements when an earthquake occurs.

It is clear that the larger fractures important for earthquake simulations are not being adequately captured in the DFN models that have been prepared for flow and transport calculations. For example, the mean radius for Kivetty is reported as 0.9 m and the radius standard deviation is 0.5 m. These fracture radii conform to a lognormal distribution. A quick analysis of these parameters suggests that only 1 in 10^9 fractures will have a radius greater than about 17.5 m and only 1 in 10^{15} fractures will have a radius greater than 47 m. Given the density of lineaments and their trace lengths, it would be surprising if there were so few large fractures.

In order to construct DFN models for the four Finnish sites, it would be necessary to collect some additional data, or to analyze existing data in new ways. The ideal data set consists of trace maps from underground tunnels at the depth of the repository. However, a combination of outcrop data and borehole data can also produce very good estimates of fracture sizes if the censoring effects are accounted for in the analysis (La Pointe et al. 1993).

This technique overcomes many of the problems that occur when fracture traces are censored by outcrop limits, trench dimensions or borehole diameter. This procedure has been applied to fracture size estimation in other high-level waste programs and for petroleum reservoir characterization studies. It is also possible to adjust fracture size distributions estimated from surface data for enhancement due to stress relief if subsurface core or borehole imagery exists.

2.2.1 Lineament data

As part of the initial siting efforts, considerable effort was put into preparing lineament maps for most of Finland. Particular attention was paid to identifying those lineaments that might be large faults. These lineaments have been mapped on a consistent basis for all of the areas surrounding the four candidate sites, and are stored in electronic form.

No additional lineament data needs to be collected in order to carry out the earthquake simulations. The existing data would need to be analyzed to see if a continuum of fracture sizes exists from the lineament scale to the outcrop scale, and if not, at what fracture size the break in scale may occur. La Pointe et al. (1998) have carried out a scaling analysis of fracture size and spatial intensity for the three generic Swedish sites, and illustrate how the data at different scales may be compared.

2.2.2 Estimates of recurrence rates

The magnitude, location and date of occurrence of earthquakes in Fennoscandia have been well studied for both instrumental and historical earthquakes. This has led to the identification of seismic zones within Fennoscandia and Finland that have their own characteristic recurrence rate parameters (for example, Båth 1979, Skordas & Kulhánek 1992, Mäntyniemi et al. 1993).

As in Sweden, there is uncertainty concerning the cause of current seismicity, and also in the number and magnitude of post-glacial faulting events during future de-glaciation.

In Fennoscandia, evidence has been put forward to relate seismicity to purely tectonic processes such as ridge-push (Slunga 1991). On the other hand, Muir-Wood (1993) presents evidence for the importance of isostatic rebound. The main difference in terms of the earthquake simulations is that the recurrence rates for ridge-push earthquakes should remain relatively constant over the next 100,000 years. Thus current seismicity provides a reasonable basis for projecting future tectonic seismicity. However, if seismicity is related to rebound, then earthquake activity is not constant within the repository performance time frame. The recurrence rates will vary according to the glacial loading and unloading cycle. This implies that recurrence rate parameters deduced from recent seismicity could overestimate earthquake activity until the next glacial cycle, and then underestimate the activity following unloading.

Current models for the future glaciation of Fennoscandia suggest that the pattern of ice loading may be similar to the previous period of glaciation. In this respect, there is a model for the location and rates of isostatic re-adjustment during a future glacial cycle. One possible way of capturing the effects of earthquakes related to rebound is to calculate the strain energy available due to rebound, and then to partition this among faults at a variety of scales in proportion to their surface areas. This would be consistent with the model proposed by Niini (1987). The model proposes that the isostatic rebound of Finland occurs along the dense mosaic of rock blocks. This allows the regional strain to be accommodated by widespread smaller scale displacement on faults defining these blocks. Since the strain energy released by an earthquake is proportional to the product of rupture area and displacement, and rupture area and displacement are correlated to surface rupture length (Wells & Coppersmith 1994), it is possible to assign a maximum amount of strain energy that each mapped lineament could accommodate. Thus, calculated strain energy for complete isostatic rebound could be estimated for subregions of Finland, or the areas surrounding the four sites, and partitioned to mapped lineaments at random only based upon the surface trace length until all of strain has been accounted for.

Post-glacial faulting may take place through a combination of tectonic processes and the glacial cycle. The energy may be produced largely through tectonic forces. The vertical load created by the ice dampens earthquake activity during the ice build up. As the ice retreats, the stored energy is released as large earthquakes.

This mechanism assumes that most of the stored energy comes from tectonic forces. It should be possible to estimate the amount of strain energy that could be stored for a particular time period based upon current plate tectonic parameters such as the rate and direction of plate movements. If all of the stored energy is released as a series of earthquakes following deglaciation, then, as in the case of rebound, the total energy could be partitioned among mapped fault lineaments. These fault lineaments would serve as the locations for the future earthquakes related to post-glacial faulting.

Another option is to rely upon the fact that in a linear elastic model, energy releases are linearly additive. The role of the ice is primarily to retard earthquakes during the ice build up prior to de-glaciation. The majority of the strain energy comes from tectonic forces. Thus the total strain energy for the complete glacial cycle is the same whether there is ice loading or not. The ice loading does not change the strain energy, it only changes the timing of the releases and the size of the individual releases. As previously noted in Section 2.1, the induced slippage would be the same whether there were one large energy release on a fault or several energy releases on the same fault that equaled the single release. Thus, extrapolating the recurrence rates for tectonically produced earthquakes may provide a reasonable forecast for the magnitude and frequency of earthquakes due to post-glacial faulting as well.

2.3 Potential difficulties

Not all of the necessary data is currently available for carrying out earthquake simulations according to the methodology outlined in Section 2.1.

The greatest area of uncertainty is in forecasting the recurrence rates for future earthquakes. The geological issues concerning the forecast of future seismicity have been discussed in the previous section. They are:

1) What is the mechanism of current earthquakes?

2) What is the role of post-glacial faulting, which may be more prevalent in Finland than in Sweden?

There are also some statistical issues as well.

Fennoscandia has low levels of seismicity, so that the historical and instrumental record of earthquakes contains relatively few events and consists of earthquakes of moderate to low magnitudes. Extrapolation to much larger earthquakes is consequently more uncertain. Thus, the third issue is:

3) How uncertain is it to extrapolate current earthquake recurrence parameters deduced from only small to moderate earthquakes to much larger earthquakes?

The final results of the earthquake calculations are sensitive to the fracture size and intensity distributions specified for the discrete fracture network models. Current DFN models developed for flow and transport simulations are not adequate for modeling earthquakes. Additional data analysis and possibly data collection is needed in order to reduce uncertainty. This leads to the fourth issue:

4) How relevant are current DFN models for the four candidate sites for earthquake studies? Should additional analysis or data collection be undertaken?

These and other questions are explored in the next section through a series of illustrative simulations.

3 CALCULATION OF CRITICAL MAGNITUDE-DISTANCE RELATIONS FOR FINNISH SITES

3.1 Overview of discrete fracture models

Some simple, illustrative earthquake simulations have been carried out for the four candidate sites. These simulations are not performance calculations, since they do not include proposed canister layouts, and they ignore the earthquake magnitude-frequency relations and the lineaments that have been mapped for the region surrounding each site. Moreover, the input DFN parameters are based on fracture statistics that were designed for use in flow and transport simulations, not earthquake calculations.

The purpose of these simulations is to further illustrate the methodology, to point out the importance of carrying out additional work on determining the fracture size distribution and intensity for the four candidate sites, and to show that only the largest faults within a few kilometers of a site are capable of producing earthquakes that could compromise canister integrity.

Discrete fracture network (DFN) models for all four Finnish sites were constructed according to the current model parameters provided by VTT (M. Laitinen, pers. comm. 1998). Table 3-2 through Table 3-5 list the parameters used for these models, which were intended for use in the construction of models for flow and transport simulations. Due to the scale of the flow models, fractures of scales of less than 1 meter were included. Most of these small fractures may be neglected for earthquake simulations. This can be seen from the following illustrative calculation:

Regressions performed by La Pointe et al. (1998) on Wells & Coppersmith's (1994) data shows that the maximum subsurface displacement associated with a fault rupture area is described by the equation:

$$Log_{10}(RA) = a + bLog_{10}(MD) \qquad \text{Equation 3-1}$$

where a and b are constants,
MD is the maximum subsurface displacement in m, and
RA is the rupture area in km^2.

Values for a and b are given in Table 3-1 as a function of fault type. Also shown in the Table are the minimum rupture area that would be required for a maximum displacement of 0.01 m, and an equivalent radius in meters. The equivalent radius is defined as the radius of a circle that has the same area as the rupture area. It is a measure of the fracture size that would be required.

***Table 3-1**. Minimum fracture rupture area and equivalent radius of earthquakes producing maximum slip of 0.01 m.*

Fault Type	**a**	**b**	**std error a**	**std error b**	**Area (Km^2) for D = 0.01 m**	**Radius (m)**
Reverse	2.162	0.637	0.140	0.318	7.733	1569
Normal	2.626	0.373	0.050	0.066	76.065	4921
Strike Slip	2.818	0.751	0.068	0.089	20.713	2568
All	2.565	0.511	0.063	0.092	34.918	3334

This Table shows that rupture areas of at least 1.5 km equivalent radius are needed for slip to exceed 0.01 m on the fault sustaining the earthquake. Since the induced slip on other fractures will be less than the slip on the fault on which the earthquake occurs, this suggests that any fracture less than 1.5 km equivalent radius is unlikely to experience more than 0.01 m of primary or induced slip during any single earthquake. While this calculation does not consider the cumulative effects of thousands of earthquakes over the next 100,000 years, it does suggest that fractures on the order of 1 m will probably not impact canister safety in any significant way during future earthquakes. Thus, the DFN models designed for flow calculations can be simplified by eliminating the thousands of very small fractures.

The minimum size considered for the simulations was chosen to make the numerical calculations sufficiently quick to be carried out within the project time frame, and also to insure that the minimum size was still well below the minimum equivalent radius shown in Table 3-1. The goal of choosing these values was to create DFN models with approximately 300 fractures. The minimum size cut-offs applied are shown in Table 3-6. For three of the sites (Kivetty, Olkiluoto, and Romuvaara) a model size of 40x40x40 m with a minimum fracture radius of 2.75 m was chosen (Table 3-2, Table 3-4 and Table 3-5). Figure 3-1 shows the visual effect of trimming the Olkiluoto fracture model from over 40000 fractures down to just the 280 largest fractures. The fourth site, Loviisa, required different parameters due to a much larger mean fracture size at that location (Table 3-3). For Loviisa, a larger model (160x160x160 m) was chosen so that fewer fractures were truncated by the model boundaries. In addition, a larger minimum fracture radius (40 m) was necessary in order to keep the number of fractures around 300.

***Table 3-2**. Kivetty Site.*

	Set 1	**Set 2**
Fisher Orientation Model:	trend = 18° plunge = 0° κ = 2.95	trend = 257° plunge = 0° κ = 3.38
Size Model	lognormal mean = 0.9 stdev = 0.5	lognormal mean = 0.9 stdev = 0.5
Intensity (P32)	1.552 m^2/m^3	0.285 m^2/m^3

***Table 3-3**. Loviisa Site.*

	Set 1	Set 2
Fisher Orientation Model:	trend = 275° plunge = 80.6° κ = 5.9	trend = 341° plunge = 0° κ = 1.8
Size Model	lognormal mean = 4.5 stdev = 12.2	lognormal mean = 4.5 stdev = 12.2
Intensity (P32)	0.697 m^2/m^3	0.855 m^2/m^3

***Table 3-4**. Olkiluoto Site.*

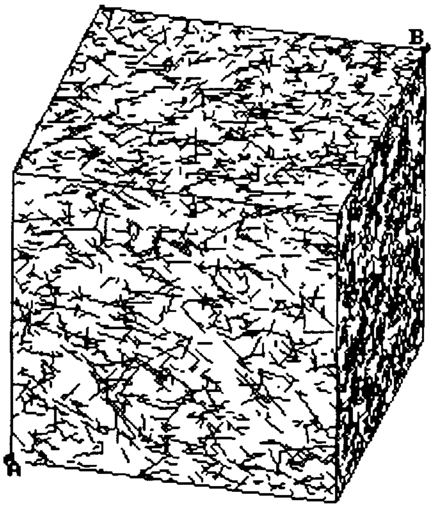
	Set 1	Set 2	Set 3
Fisher Orientation Model:	trend = 330° plunge = 51° κ = 4.9	trend = 167° plunge = 65° κ = 6.2	trend = 360° plunge = 90° κ = 0.0001
Size Model	lognormal mean = 0.9 stdev = 0.5	lognormal mean = 0.9 stdev = 0.5	lognormal mean = 0.9 stdev = 0.5
Intensity (P32)	0.829 m^2/m^3	0.369 m^2/m^3	0.800 m^2/m^3

***Table 3-5**. Romuvaara Site.*

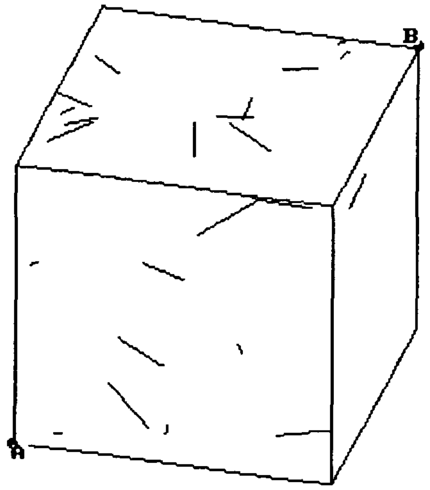
	Set 1	Set 2	Set 3	Set 4
Fisher Orientation Model:	trend = 64° plunge = 36° κ = 30.0	trend = 48° plunge = 66° κ = 1.6	trend = 61° plunge = 34° κ = 11.5	trend = 31° plunge = 59° κ = 1.3
Size Model	lognormal mean = 0.65 stdev = 0.70	lognormal mean = 0.65 stdev = 0.70	lognormal mean = 1.5 stdev = 0.45	lognormal mean = 1.5 stdev = 0.45
Intensity (P32)	0.114 m^2/m^3	0.477 m^2/m^3	0.422 m^2/m^3	0.506 m^2/m^3

***Table 3-6**. Size cutoffs and number of fractures for each DFN model.*

Site	Model Size	Number of fractures with no cutoff	Minimum Size cutoff (m)	Average number of fractures with cutoff
Kivetty	40x40x40	~38000	2.75	248
Loviisa	160x160x160	~28000	40.0	368
Olkiluoto	40x40x40	~40000	2.75	280
Romuvaara	40x40x40	~13700	2.75	382



a) Olkiluoto, all fractures.



b) Olkiluoto: $R_{min} = 2.75m$

A: (20m, -20m, -20m)
B: (-20m, 20m, 20m)

***Figure 3-1**. Effects of truncation on Olkiluoto DFN Model.*

3.2 Modeling results

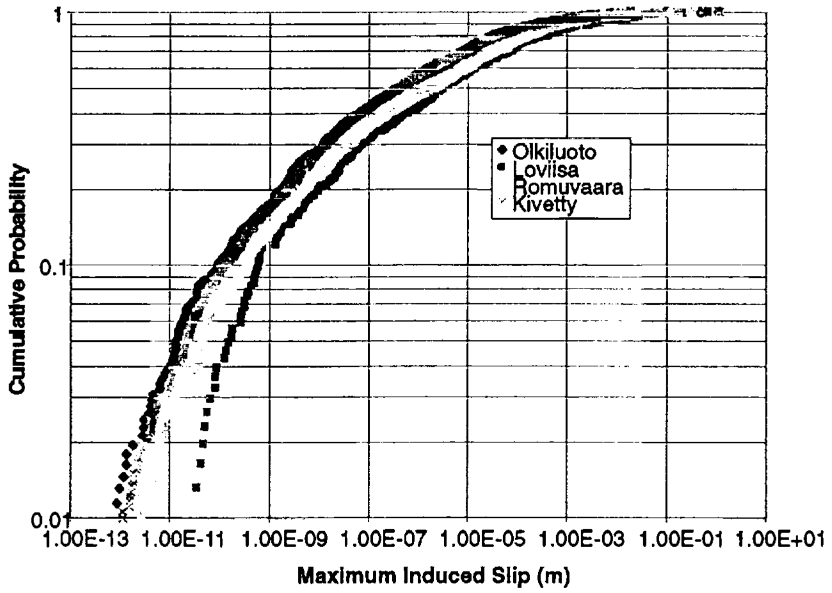
For each site, several hundred earthquakes were simulated with epicenters located within a distance range of 50 m to 100 km of the DFN model centerpoint. Earthquake magnitudes varied between 1.0 to 8.0. The relation between the displacement occurring over the fault rupture surface and the magnitude of the earthquake was based on the regressions reported in La Pointe et al. (1997), in which the logarithm of the displacement is a first-order polynomial function of the magnitude. For each Poly3D simulation the mean, median, and maximum induced slip were calculated. These statistics were based on the induced displacements of all fractures, not just those that might intersect canister holes, since explicit canister layout designs were not incorporated for these illustrative calculations.

One measure of the accuracy of the Poly3D solution is the *condition number*. The condition number is the ratio of the largest matrix elements to the smallest matrix elements (Press et al. 1992). A matrix is singular if its condition number is infinite and ill-conditioned if it is too large ($>10^6$ for single precision programs). Initially, all Poly3D results were considered valid; however, it eventually became clear that in simulations in which the matrix conditioning number was greater than 1×10^7, anomalously high secondary slips were being calculated. Therefore, the results for 30 simulations for Kivetty, 19 for Loviisa, and 18 for Romuvaara were eliminated from consideration.

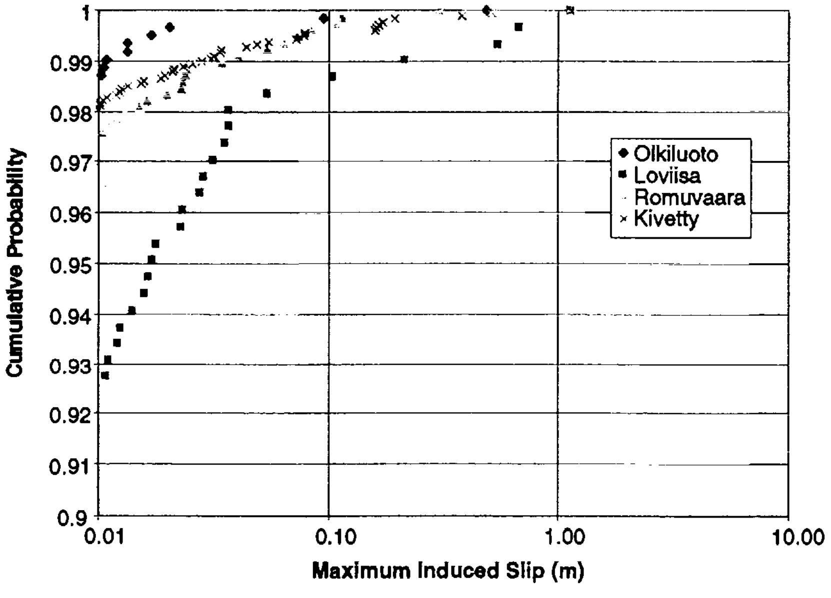
The results of the Poly3D modeling are presented in three formats. First, the cumulative probability of the maximum induced slip for each site (Figure 3-2) is calculated. This is done by sorting the maximum induced slips for each site, ranking, and then divide the rank by the total number of events. Figure 3-2a shows that 80% of the induced slips are less than 1 mm. A detail of the largest slips (Figure 3-2b) shows that Loviisa tends to have the greatest amount of induced slip, while Olkiluoto has the least. Since the earthquake simulation parameters are the same for all four sites, the differences must be due to differences in the DFN model parameters used, as discussed in the end of this section.

In order to derive an earthquake-distance relationship, a different type of plot was made (Figures 3-3 through 3-6). In these plots, the maximum induced slip was plotted against the distance to the center of the earthquake for each simulated event. These figures show, as expected, a clear relation between maximum slip and distance to an earthquake. The considerable scatter is due to the fact that the displacement on the fault has not been factored out of this graph. For any particular distance, earthquakes ranging in magnitude from magnitude 1 to magnitude 8 could have occurred. Regardless of the magnitude, however, no events further than about 10 km exceed a 10 cm induced slip threshold for all sites.

A second way to examine the effects of earthquakes is to plot the induced displacements as a function of both strain energy released by the earthquake and epicentral distance. Strain energy is a function of the product of the shear modulus of the rock hosting the fault, the rupture surface area, and the dislocation or displacement that occurs over the rupture area. Since the shear modulus is constant for all of the simulations carried out, the variability in strain energy is only a function of the product of rupture area and primary fault displacement.



a) Cumulative probability



b) Detail of Cumulative Probability for Largest Induced Slips

Figure 3-2. Cumulative probability of induced slip.

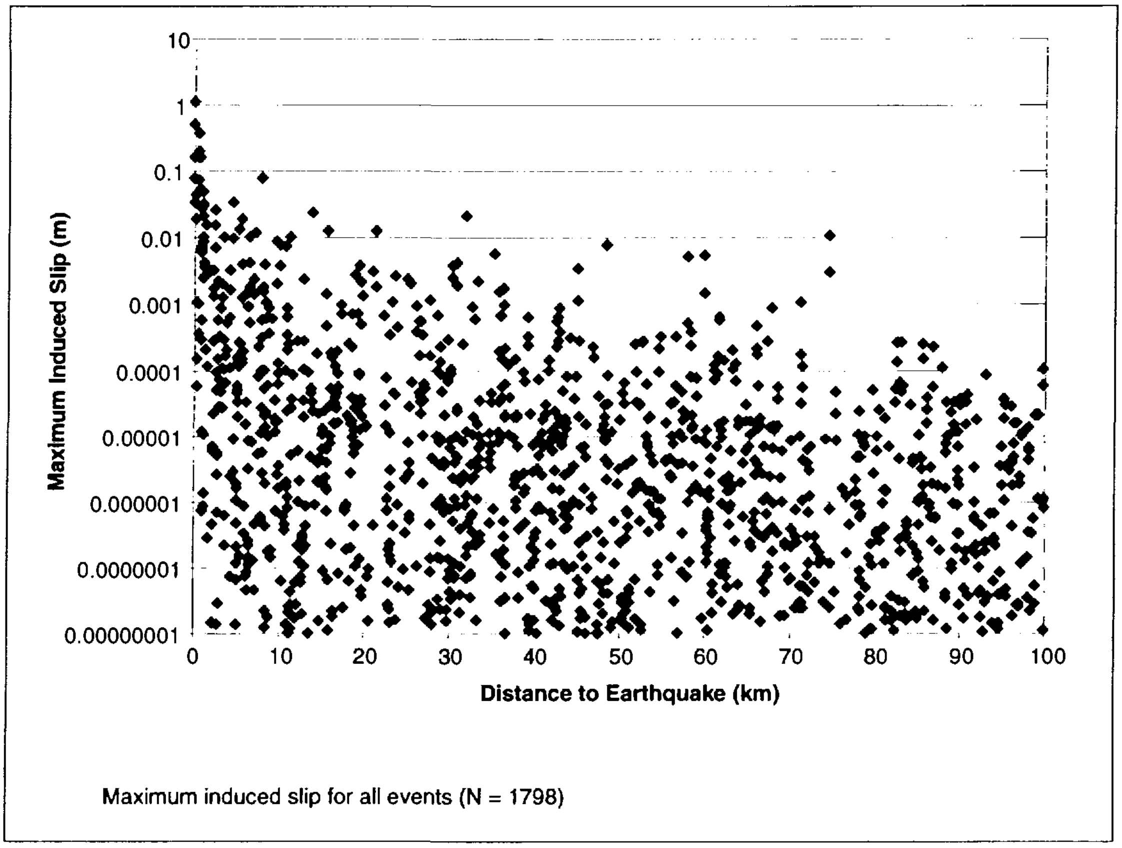


Figure 3-3. Results for Kivetty.

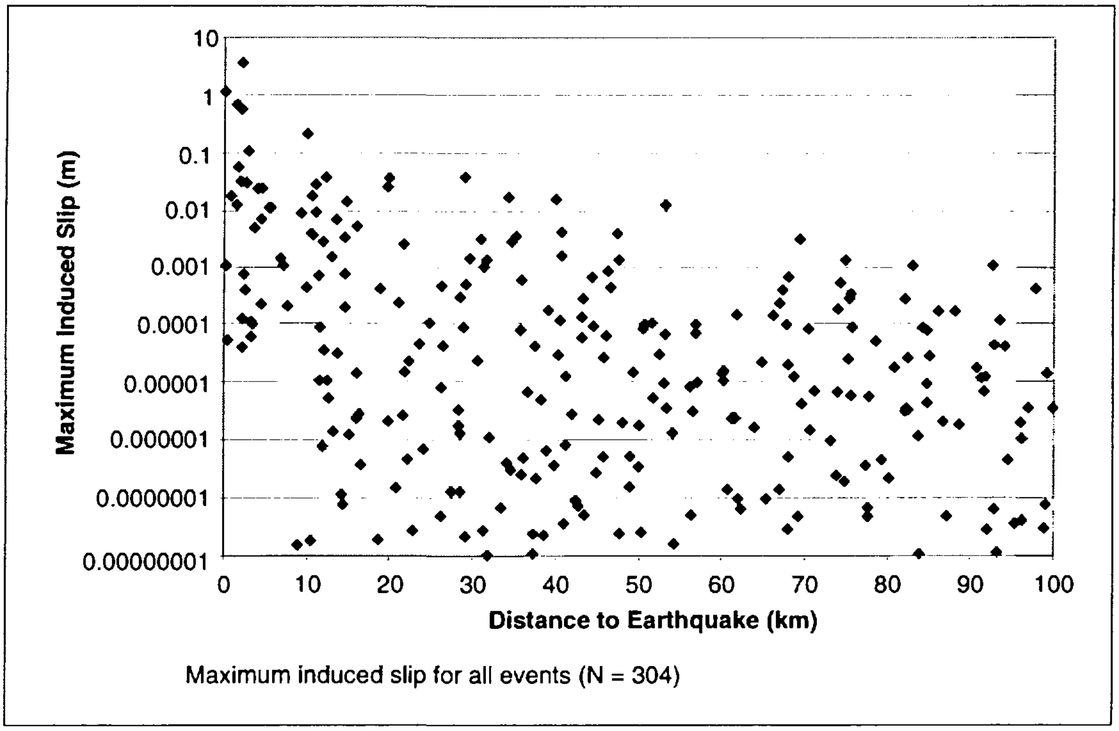
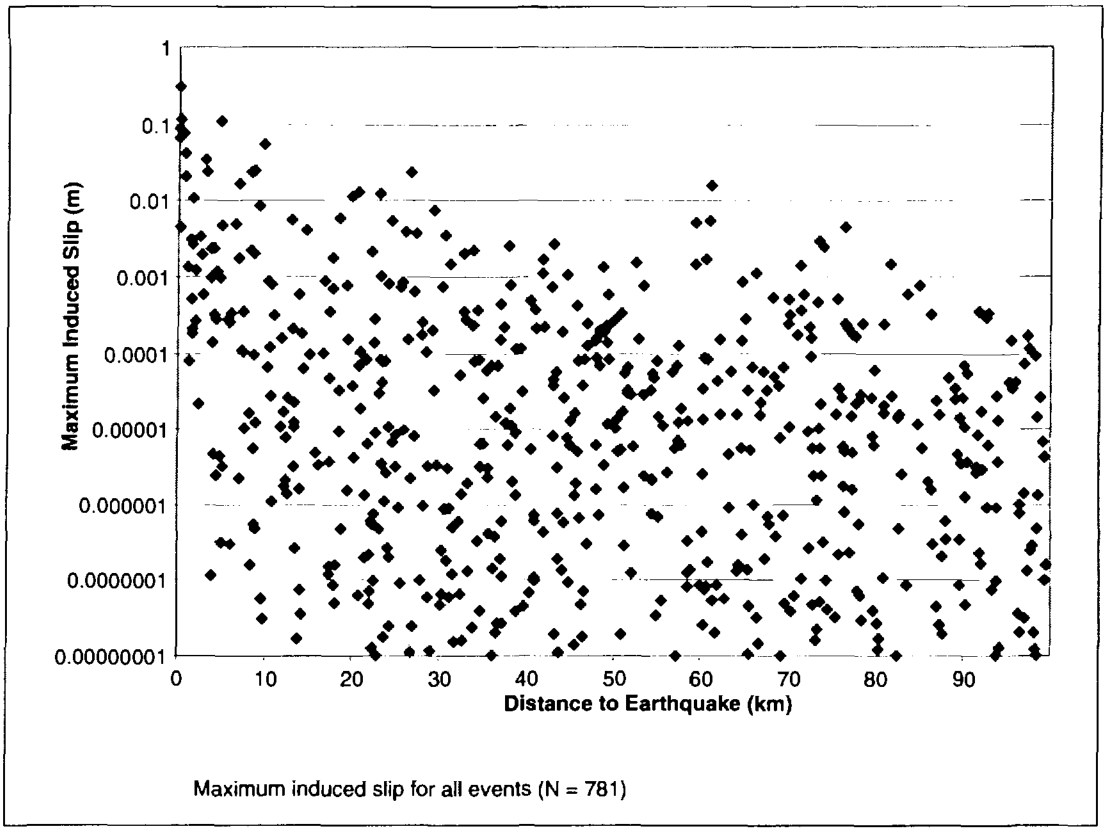
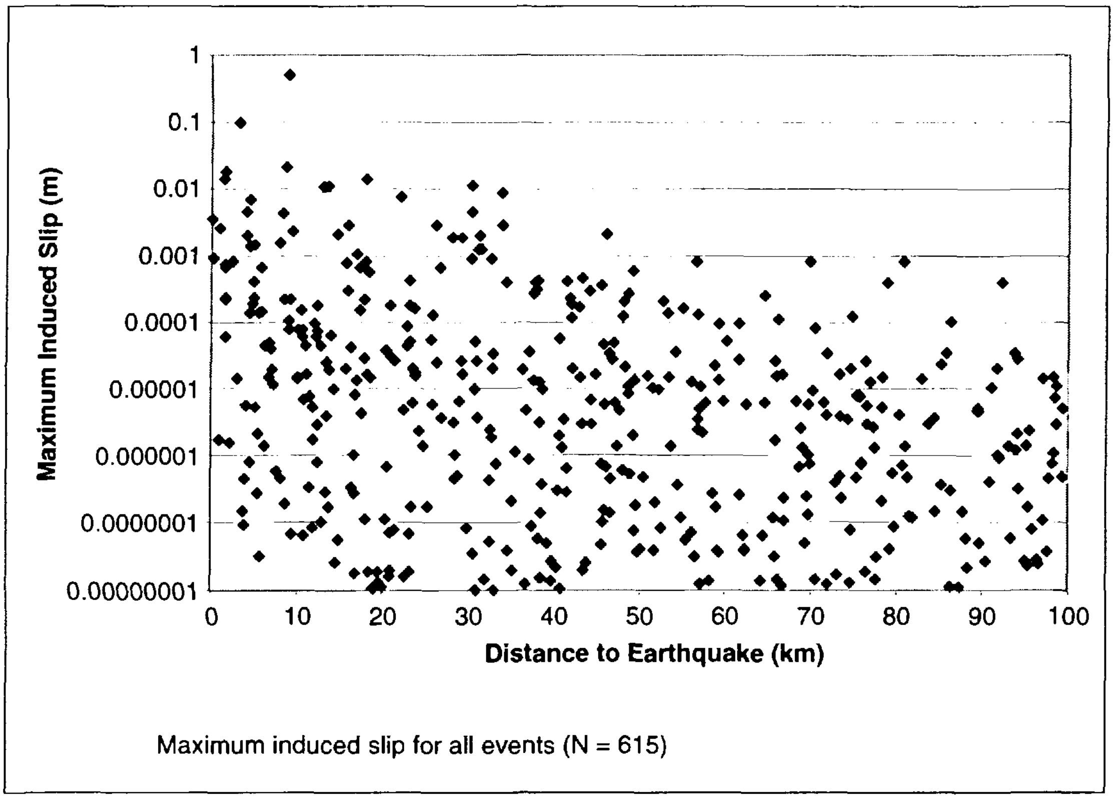


Figure 3-4. Results for Loviisa.



Maximum induced slip for all events (N = 781)

Figure 3-5. Results for Romuvaara.



Maximum induced slip for all events (N = 615)

Figure 3-6. Results for Olkiluoto.

Figures 3-7 through 3-10 show colored contour plots of induced displacement as a function of epicentral distance and the product of displacement and rupture area (strain energy). Induced displacements greater than 10 cm are colored red. The blank areas of these figures are due to the low probability of these parameter combinations in the number of simulations carried out. If the number of simulations were increased, it is likely that the blank areas corresponding to low magnitudes and nearby epicenters would contain results.

As expected, the largest induced displacements occur in the upper left corners (small epicentral distances and a large strain energy) of all four contour plots. In addition, the relationship between epicentral distance, maximum induced slip, and earthquake size is predictable. This is demonstrated by the fact that each contour line on Figures 3-7 through 3-10 could be approximated by a straight, diagonal line. Fracture and fault orientations introduce a relatively small amount of noise to the contours. There are some differences between the sites. The contours for Loviisa are noticeably shifted to the lower right corner of the plot, indicating that more distant earthquakes can cause more damage. This is due to larger fracture sizes at this site.

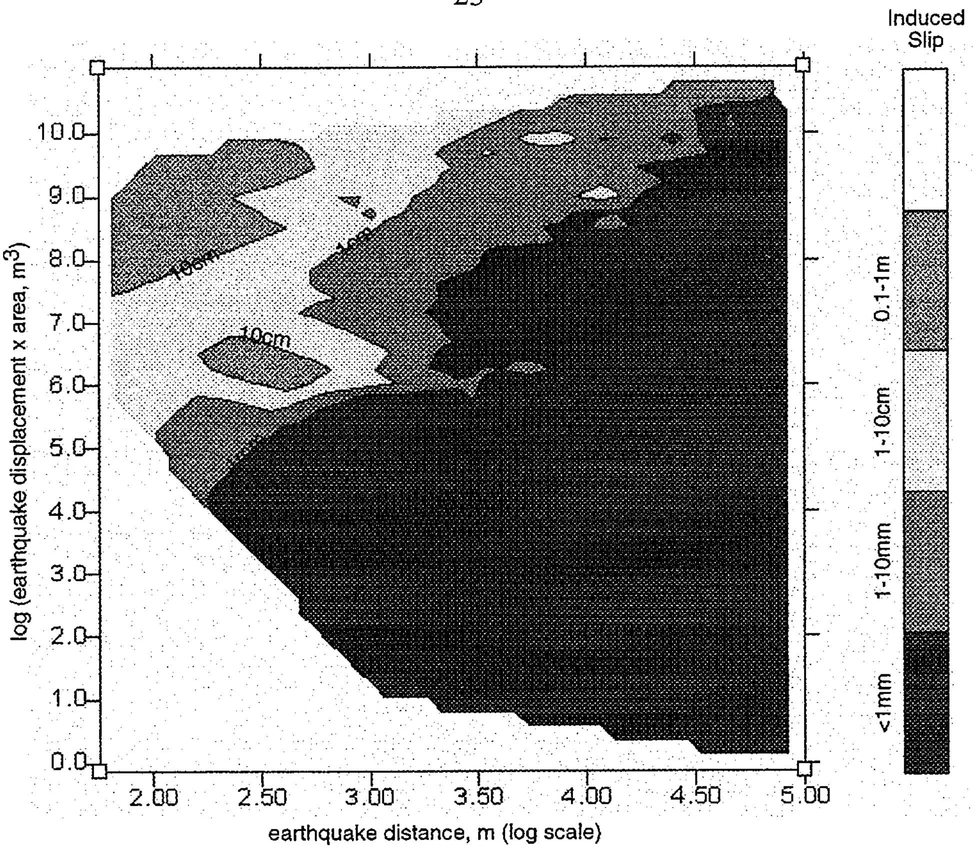


Figure 3-7. Earthquake size vs. distance for Kivetty.

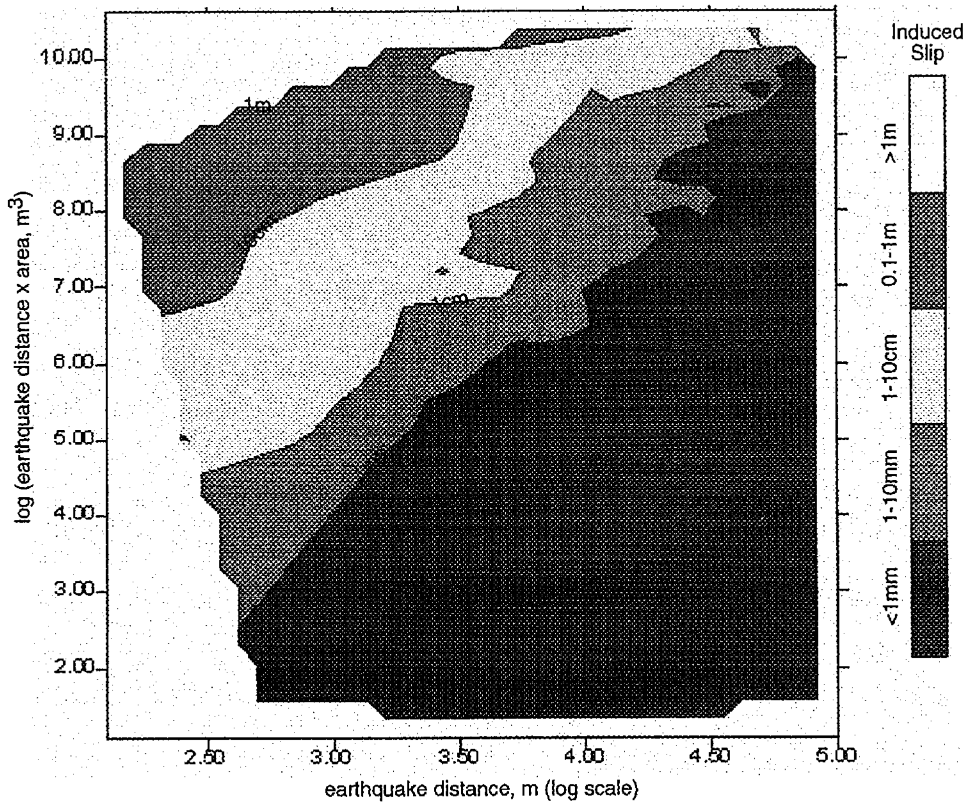


Figure 3-8. Earthquake size vs. distance for Loviisa.

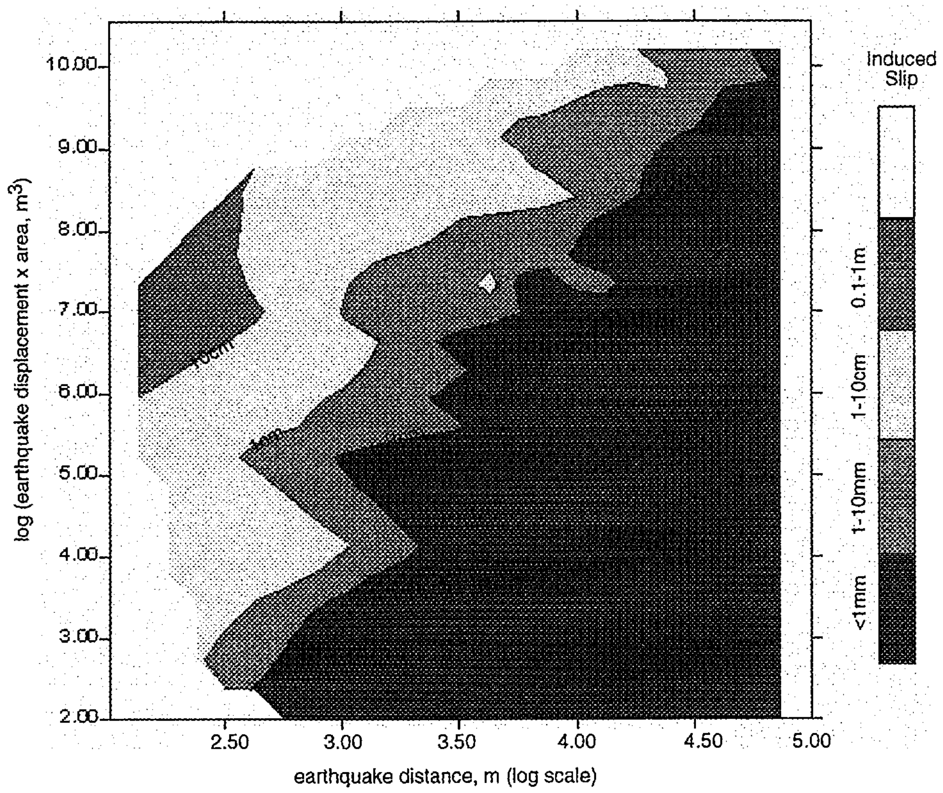


Figure 3-9. Earthquake size vs. distance for Romuvaara.

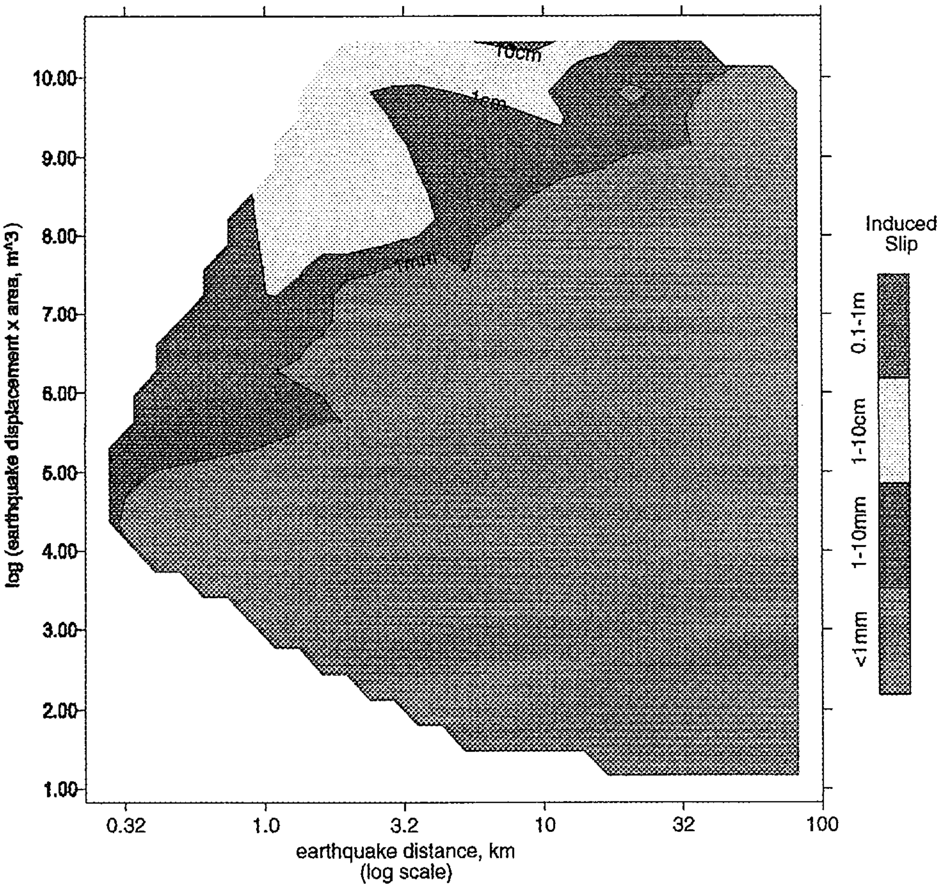


Figure 3-10. Earthquake size vs. distance for Olkiluoto.

4 CONCLUSIONS & RECOMMENDATIONS FOR POSSIBLE FUTURE STUDIES

These illustrative earthquake simulations illustrate the impacts that fracture size, intensity and orientation can have on calculated displacements. As a general conclusion, the bigger the fractures, the greater will be the induced slip. As fracture intensity increases, more fractures are likely to intersect canister holes, which would diminish safety, all other factors being the same. Moreover, the fracture orientations also play a role, although the current studies do not indicate any general rule about what orientations are most favorable. Further analysis of the DFN models and simulated earthquakes would provide more information on the characteristics of the fractures with the largest induced slips and the earthquakes that induce the largest slips.

These results show the importance of accurately determining the orientations, size distribution and intensity of fractures that are likely to intersect canister holes at each candidate site. The DFN model parameters derived for flow and transport modeling may prove inadequate for the following reason: the scale range of fracturing important for hydrological modeling is on the order of centimeters to a few tens of meters. This is because the DFN models are nested within larger continuum models. The current earthquake simulations have illustrated the importance that larger fractures can have. In order to carry out earthquake simulations for each candidate site, it would be useful to first determine the scaling properties of fracture size as was done for the earthquake calculations for the generic Swedish repository study sites (La Pointe et al. 1998). These scaling studies make it possible to extrapolate outcrop, borehole or limited underground cavern data that is limited in scale to the larger scales of interest with increased confidence. The accuracy of the final results will depend upon the accuracy of this extrapolation.

Because fracture orientation plays a role in the calculated secondary displacements, it may be possible to preferentially orient canisters in order to reduce the intersections with the less favorably oriented fractures. These investigations would require incorporation of all site-specific fracture and earthquake recurrence data, and would be appropriate for possible future earthquake simulation studies.

Earthquake magnitude-frequency relationships for each candidate site are both important and uncertain. It is particularly important to determine the importance of post-glacial faulting; whether current earthquake activity results from tectonic ridge-push forces or from rebound; and to assess the quantity of strain energy that might be available for seismogenic release due to either mechanism. This might be accomplished using the approach suggested in Section 2.2.2.

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