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Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results

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Abstract

The Baltic Shield is one of the most tectonically stable areas in the world. In Sweden, earthquakes have only on a few occasions exceeded magnitude 4 in modern times. Nevertheless, the safety case for a deep repository for spent fuel includes an earthquake scenario, as earthquakes with much greater magnitudes occurred in northern Sweden during the most recent deglaciation period some 9000–10 000 years ago when faults re-activated and ruptured the surface.

An important safety issue for the deep repository is that future displacements in the rock should be less than 0.1 m at the precise location where the engineered canisters containing the waste are emplaced.

The fact-finding for this project was performed by conducting interviews, literature surveys, Internet searches, by sending letters to some 60 organisations and by site visits to Japan, Taiwan and South Africa.

The most important conclusions of this study are:

- The buffer and canister shake as a solid body without producing excess shear stresses or liquefaction of the buffer.
- The data emanating from faults intersecting tunnels show that creation of new fractures is confined to the immediate vicinity of the reactivated faults and that deformation in host rock is rapidly decreasing with the distance from the fault. By selection of appropriate respect distances the probability of canister damage due to faulting is further lowered.
- Respect distances might be considerably smaller than predicted by numerical modelling.

Summary

The Baltic Shield is one of the most stable areas in the world. Earthquakes have only on a few occasions exceeded magnitude 4 in Sweden in modern times. The safety case for a deep repository for spent fuel however includes an earthquake scenario due to the following reason: Earthquakes with much greater magnitudes occurred in northern Sweden during the most recent deglaciation period some 9000–10 000 years ago when re-activated faults ruptured the surface. One of the most prominent evidences is the Pärvie fault in Lapland, Sweden. The displacements exceeded 10 m in places and occurred over distances of around 150 km.

The deep repository is designed to keep radiation well below the natural, ambient radiation for any time in the future. The safety function is achieved by a combination of engineered and natural barriers. One important safety issue is that future displacements in the rock should be less than 0.1 m at the precise location where the engineered canisters containing the waste are emplaced in the rock. Larger displacements could damage the canister that is designed to be tight for several 100 000 of years. SKB now re-visits the issues of seismic effects on underground facilities to supplement and update previous work. The project *Effects of Earthquakes on Underground Facilities* aims to re-compile field evidences of seismic damage on underground facilities, to shed additional light on the matter of friction loss in bedrock due to water-level changes and finally to find suitable ways to inform concerned citizens on the matter.

The fact-finding was carried out in the form of interviews, literature surveys, Internet searches and by sending letters to some 60 organisations and researchers asking for co-operation. Based on the findings, including site visits to Japan, Taiwan and South Africa, several important facts and data have been collected.

The most important conclusions are:

Earthquake impact during the *pre-closure* phase:

- Damage due to shaking in an underground facility may occur if the peak ground acceleration exceeds 2 m/s^2. Sweden is located in the Baltic Shield that is seismically rather silent and will remain so in the foreseeable future. Seismic hazard has been calculated for Sweden and it is concluded that Peak Ground Accelerations (PGA) greater than 2 m/s^2 is very unlikely the next coming 50-year period, in which the repository is planned to be constructed and operated.
- Damage due to shaking is very rare in underground facilities. Where such damage has occurred, the rock is either very poor or subject to very high stresses. None of these conditions will prevail in the Swedish repository. Most damage is also correlated to the presence of faults and the spent fuel will not be deposited in or close to important faults.
- Mining-induced earthquakes are known to cause damages in the mines. At the repository site it might be possible to experience local rock burst problems due to heterogeneous rock strengths and varying rock stresses. It is expected that these events, in case they appear, will take place when the tunnels are excavated rather than at the time of canister deposition.

Earthquake impact during the *post-closure* phase:

- The present seismic activity in Sweden is expected to increase considerably in connection to the retreat of ice sheets in future glaciations. Peak ground accelerations may exceed 2 m/s^2 in association to large earthquakes. However, the effects of shaking, such as fallouts, cracking of lining are reduced since all tunnels will be backfilled by crushed rock and bentonite.

- The presence of the repository will not trigger earthquakes as the extraction ratio of the openings is very low compared to open stopes in a mine. There are also evidences for mines at great depth, that backfilling lower the mining-induced seismic activity compared to the situation when tunnels are not backfilled.

- The buffer and canister shake as a solid body without producing excess shear stresses or liquefaction of the buffer. Water-level changes will occur due to earthquakes but most of the changes are temporary and water-levels will return to their original values within a few months. The density of the buffer around the canister is high enough to prevent liquefaction due to shaking.

- The predominant brittle deformation of a rock mass will be reactivation of pre-existing fractures. The data emanating from faults intersecting tunnels show that creation of new fractures is confined to the immediate vicinity of the reactivated faults and that deformation in host rock is rapidly decreasing with the distance from the fault. By selection of appropriate respect distances the probability of canister damage due to faulting is further lowered.

- Data from deep South African mines show that rocks in a environment with non-existing faults and with low fracture densities and high stresses might generate faults in a previously unfractured rock mass. The Swedish repository will be located in fractured bedrock, at intermediate depth, 400–700 m, where stresses are moderate. The conditions to create these peculiar mining-induced features will not prevail in the repository environment. Should these faults anyhow be created, the canister is designed to withstand a shear deformation of at least 0.1 m. This corresponds to a magnitude 6 earthquake along the fault with a length of at least 1 km which is highly unlikely.

- Respect distance has to be site and fault specific. Field evidence gathered in this study indicates that respect distances may be considerably smaller (tens to hundreds of m) than predicted by numerical modelling (thousands of m). However, the accumulated deformation during repeated, future seismic event has to be accounted for.

Sammanfattning

Den Baltiska Skölden hör till världens mest stabila områden. Jordskalven har bara tillfälligtvis överskridit magnitud 4 i modern tid. Säkerhetsanalysen för djupförvaret inkluderar emellertid ett jordskalvscenario av följande skäl: Mycket kraftigare jordskalv inträffade i norra Sverige i samband med den senaste isavsmältningen för 9000–10 000 år sedan, då reaktiverade förkastningar skar markytan. Ett av de mest tydliga bevisen är Pärvie-förkastningen i Lappland. Förskjutningarna överskred ställvis 10 m och skedde över avstånd av 150 kilometer.

Djupförvaret är utformat så att strålningen är mycket lägre än den naturliga bakgrundsstrålningen. Säkerheten fås genom att kombinera ingenjörsbarriärer med den naturliga barriären. En viktig säkerhetsfråga är att möjliga förskjutningar i berget ska vara mindre än 0.1 m där kapseln med avfall placeras i berget. Större förskjutningar skulle kunna skada kapseln som är utformad att vara tät i 100 000-tals år. SKB genomför nu ytterligare en studie om seismisk påverkan på undermarksanläggningar för att komplettera och uppdatera tidigare arbeten. Projektet *Jordskalveffekter på undermarksanläggningar* syftar till att sammanställa fältdata där seismiska effekter skadat undermarksanläggningar, erhålla ytterligare information om eventuellt minskad friktion i bergmassan vid jordskalv genom vattentrycksförändringar och vidare att finna lämpliga vägar att informera den intresserade allmänheten i dessa frågor.

Faktainsamling har skett genom intervjuer, litteratursökningar, sökning via Internet, genom cirkulärbrev till ett 60-tal organisationer och forskare och genom studieresa till Japan, Sydafrika och Taiwan.

De viktigaste slutsatserna följer:

Jordsskalvseffekter innan förvaret försluts

- Skador orsakade av vibrationer i en undermarksanläggning kan ske om accelerationen vid markytan överskrider 2 m/s^2. Sverige är beläget i den Baltiska Skölden, i ett lågseismiskt område, och det bedöms mycket osannolikt att markacceleration > 2 m/s^2 inträffar under den kommande 50-årsperioden då djupförvaret anläggs och är i drift.
- Skador orsakade av vibrationer är mycket sällsynta i undermarksanläggningar. Där sådana påträffas, är antingen berget mycket svagt eller utsatt för mycket höga spänningar. Ingendera av dessa situationer uppstår i det svenska djupförvaret. Största delen av skador sker också vid förkastningar; det använda kärnbränslet deponeras inte i eller nära förkastningar.
- Gruv-relaterade skalv orsakar ibland skador i gruvor. Vid platsen för djupförvaret är det möjligt att smällberg påträffas lokalt med hänsyn till den heterogena bergmassans hållfasthet och de varierande bergspänningarna. Det antas att dessa effekter i så fall uppstår vid bergbyggnaden hellre än då det använda bränslet deponeras.

Jordsskalvseffekter efter det att förvaret är förslutet

- Nuvarande seismisk aktivitet i Sverige förväntas öka avsevärt i samband med isavsmältning vid kommande istider. Största markacceleration kan överskrida 2 m/s^2 i samband med stora jordskalv. Effekter av vibrationer, som bergutfall, sprickbildning i bergförstärkningar är reducerade, eftersom tunnlarna är återfyllda med krossat berg och bentonit.

- Djupförvaret i sig inducerar inte jordskalv, eftersom den planerade utbrytningsgraden är mycket lägre än i en gruva med öppna brytningsrum. Det finns också indikationer, vid gruvbrytning på stora djup, att återfyllnad sänker den inducerade seismiska aktiviteten jämfört med då tunnlar inte är återfyllda.

- Buffert och kapsel vibrerar som en stelkropp utan att skapa överskott av skjuvspänningar eller att bufferten övergår i ett flyttillstånd (liquefaction). Vattenståndsförändringar sker som ett resultat av jordskalv, men största delen av förändringarna återgår till ursprungliga värden inom några månader. Buffertens densitet runt kapseln är tillräckligt hög för att hindra uppkomst av flyttillstånd.

- Bergmassans spröda deformation sker företrädesvis som reaktivering av redan existerande sprickor. Data från förkastningar som skär tunnlar visar att ny sprickbildning sker i omedelbar anslutning till de reaktiverade förkastningarna och att deformationen i berget kraftigt avtar med avstånd från förkastningen. Genom lämpligt val av respektavstånd, är sannolikheten för en kapselskada på grund av förskjutningar ytterligare reducerade.

- Data från djupa sydafrikanska gruvor visar att förkastningar kan ske i ett tidigare ”intakt berg”. Sådana händelser har skett i miljöer fria från förkastningar, med låga sprickfrekvenser och höga spänningar. Det svenska djupförvaret byggs på ett djup av 400–700 m där bergspänningar är måttliga och där det också finns förkastningar och sprickor. Förutsättningarna för att skapa dessa ovanliga, gruvrelaterade förkastningar föreligger därför ej i den planerade förvarsmiljön. Om dessa ändå mot förmodan skapas, är kapseln utformad att klara en bergförskjutning av åtminstone 0.1 m. Detta motsvarar ett jordskalv med magnituden 6 längs en förkastning med en längd av åtminstone 1 km, vilket bedöms som osannolikt.

- Respektavstånd ska vara specifikt för varje plats och förkastning. De fältdata som samlats i denna studie pekar på att respektavstånd kan vara avsevärt mindre (tiotals till hundratals m) än det som förutsägs av numeriska beräkningar (tusentals m).

Contents

1 Introduction

Swedish Nuclear Fuel and Waste Management Co (SKB) is the responsible, implementing organisation for all radioactive wastes generated in Sweden. Final disposal of spent nuclear fuel is planned to commence in 15 years of time. On-site investigations to license one of two potential sites will start in year 2002.

SKB has for almost 20 years executed a comprehensive, geoscientific research and development program including e.g. theoretical studies and field studies in neotectonics and seismology. The basic information is available in open SKB Technical Reports published by SKB or in scientific papers published in international journals. The reader is referred to the website www.skb.se for additional information. One previously studied issue is the potential for damage on underground facilities due to seismic effects. SKB published a literature study more than 10 years ago /Röshoff, 1989/ and now re-visits the issues of seismic effects on underground facilities to supplement and update previous work. The project *Effects of Earthquakes on Underground Facilities* aims to re-compile field evidences of seismic damage on underground facilities, to shed additional light on the matter of friction loss in bedrock due to water-level changes and finally to find suitable ways to inform concerned citizens on the matter.

It might appear surprising that there are concerns for earthquakes in one of the most tectonically stable areas in the world – the Baltic Shield. Only on a few occasions in modern times has earthquakes exceeded magnitude 4 in Sweden. Yet, analysis of the long-term safety of the deep repository includes an earthquake scenario because it has been demonstrated that earthquakes with much greater magnitudes have occurred in northern Sweden during the most recent deglaciation period some 9000–10 000 years ago. One of the most prominent evidences is the Pärvie post-glacial fault in Lapland, Sweden /Lundqvist and Lagerbäck, 1976/. The displacements exceeded 10 m in places and occurred over distances of around 150 km (Figure 1-1).

The rather lengthy introductory 1st chapter provides the general technical background for treating the following issues:

- What should the repository protect and for what time-scales?
- How can an earthquake affect the repository?
- What are typical risks for earthquakes in Sweden?
- How are tunnels and underground facilities constructed in Sweden and elsewhere in the world?
- How was the present study planned, organised and performed?
- How will the results of this study be published?

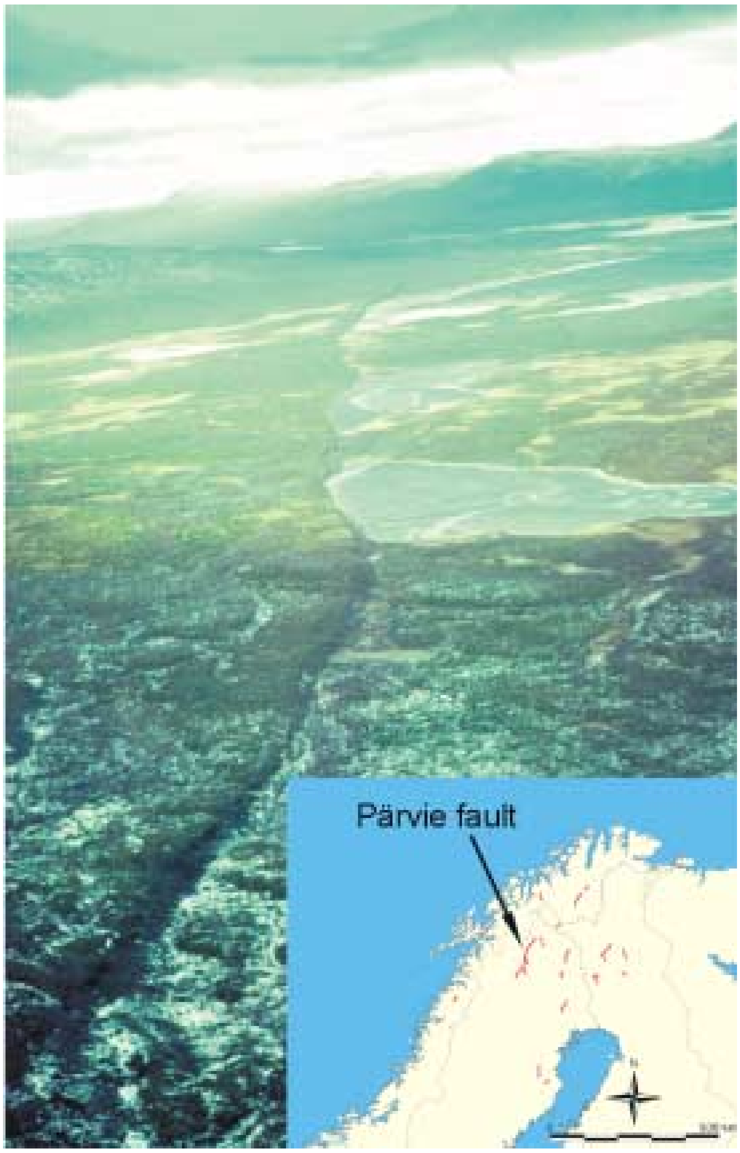


Figure 1-1. *Air-photo over the Pärvie-fault, Lapland, Sweden. It displaced in connection to the last deglaciation some 9000–10 000 years ago, probably associated with strong earthquakes, /Lagerbäck, 1978/. The fault extends for around 150 km (see insert) and the scarp height is up to 10 m in places. The insert shows the location of post-glacial faults in Northern Europe /After SKB, 1995/.*

The present study is a compilation of many sources from many countries and it has been difficult to unify the nomenclature from all these sources published over a period of some 30–50 years. Nomenclature adopted for damage due to earthquakes and magnitudes are described in Appendix A. The vibrations caused by the earthquake are denoted "shakings", as this term seems to be preferred in literature. In this paper, the preferred term for geological discontinuities is "fractures", covering cracks, fissures, joints etc. in the rock. By "fracture zone" we intend a zone in which the fracture intensity is much higher than in the adjacent rock. By "fault" we mean a fracture or fracture zone along which there has been displacement on the sides relative to the one another parallel to the fracture. Right-lateral slip (dextral) is when the apparent movement of the side opposite the observer is the to the right and left-lateral (sinistral) when the apparent movement is to the left.

1.1 Description of a deep repository for spent fuel

Nuclear power plants generate radioactive wastes that do not constitute a health hazard if properly managed. Sweden has already constructed an underground final repository for low- and medium-level waste and plans are in progress to construct a deep repository for high level wastes such as spent nuclear fuel. The spent fuel is the most hazardous waste as it is very radioactive for long time periods.

The radiotoxicity of the quantity of ore that is used to produce 1 tonne of spent fuel is compared to the radiotoxicity of the nuclear fuel in Figure 1-2. The radiotoxicity of the spent fuel decays down to the level of the naturally occurring uranium ore after about 100 000 years.

Several options for disposal have been explored but there is an international consensus that geological disposal is the preferred method for safe disposal /OECD/NEA, 1995/.

The Swedish solution, the KBS-3 method, is primarily designed to isolate the waste within the engineered barriers. If the isolation function should for any reason fail in any respect, a secondary purpose of the repository is to retard the release of radionuclides. This safety is achieved with a system of barriers Figure 1-3. The fuel is placed in corrosion-resistant copper canisters. Inside the five-meter-long canisters, a cast iron insert provides the necessary mechanical strength. A layer of bentonite clay, surrounding the canisters, protects the canister mechanically in the event of small rock movements and prevents groundwater and corrosive substances from reaching the canister. The clay also effectively adsorbs many radionuclides that could be released should the canisters be damaged. The canisters with surrounding bentonite clay are emplaced at a depth of about 400–700 m below surface in crystalline bedrock, where mechanical and chemical conditions are stable in a long-term perspective. Should any canister be damaged, the chemical properties of the fuel and the radioactive materials, for example their poor solubility in water, put severe limitations on the transport of radionuclides from the repository to the ground surface. This is particularly true of those elements with the

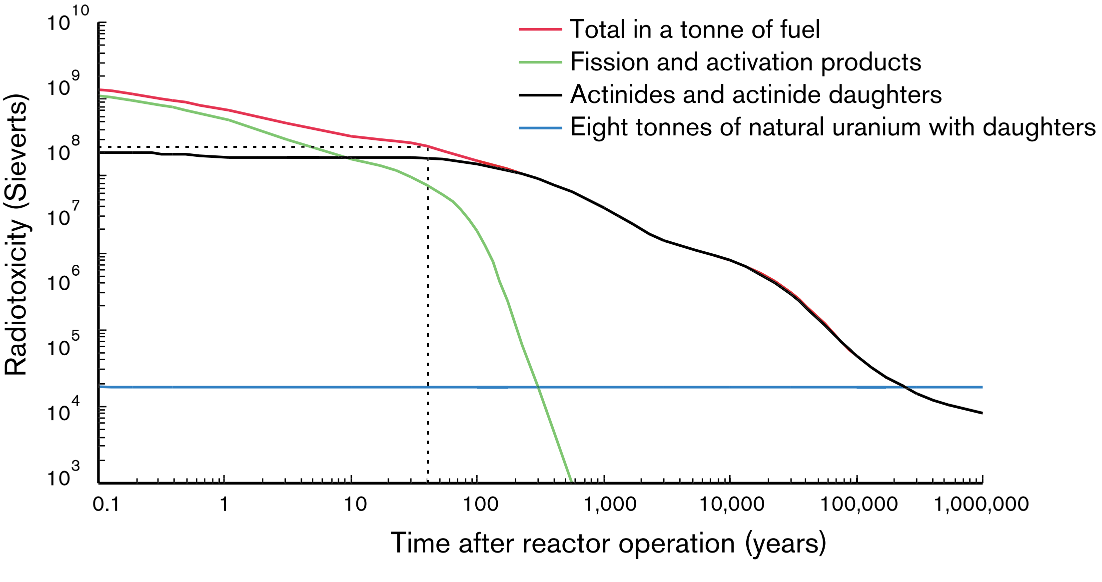


Figure 1-2. *Radiotoxicity of the waste as a function of time after discharge from the reactor for Swedish Boiling Water Reactor fuel with a burnup of 38 MWd/t U. Radiotoxicity pertains to ingestion via food. After 30 to 40 years of interim storage, the fuel will be deposited in the final repository /From SKB, 1999a/.*

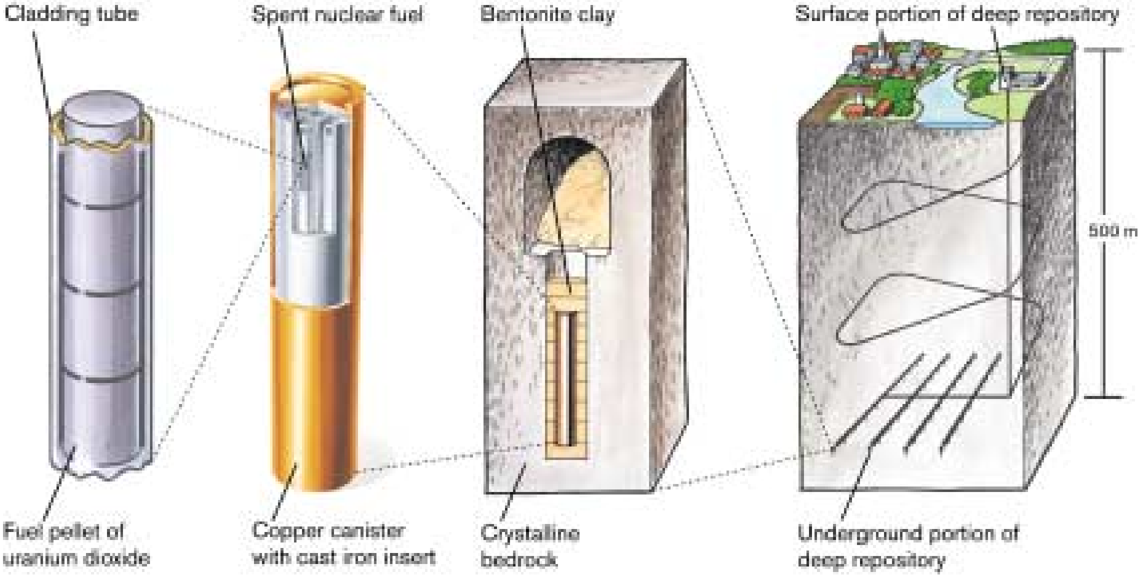


Figure 1-3. *The KBS-3 system to safely dispose of spent nuclear fuel. The picture shows the KBS-3 alternative when the canister is deposited vertically. SKB is also studying the feasibility of horizontal deposition of the canisters.*

highest long-term radiotoxicity, such as Americium and Plutonium. The repository is thus built up of several barriers, which support and complement each other. The safety of the repository must be adequate even if one barrier should be defective or fail to perform as intended. This is the essence of the multiple barrier principle.

The safety regulations decided by the authorities require that the maximum radiation possible for any foreseeable event should be orders of magnitude below the naturally occurring radiation for all the future time when the repository might be a health hazard. The scrutiny of the safety is a demanding task. The reader is referred to /SKB, 1999a/ for the most current published safety analysis of the Swedish KBS-3 method.

1.2 Statement of problem

There are several problems to explore concerning possible earthquake influence on the repository. In the broad sense we can distinguish problems before the repository is closed and problems that may occur after the spent fuel is deposited and the repository is closed.

Possible issues before closure

- Damage due to shaking before the repository is closed. The shaking may cause rock fall and loss of function on equipment for the transport and deposition of the spent fuel.

Possible issues after closure

- Damage could occur on the canister since the earthquake could create a pulse of high water pressure in addition to the dynamic stresses created by the earthquake.
- Damage could occur due to shaking; shaking could cause liquefaction of the bentonite (the bentonite turns from a solid to a liquid phase) so it cannot protect the canister properly.
- Damages due to faulting; faulting could create new fracturing and reactivate previously existing fracture zones and fractures. In case fractures crossing the deposition hole slip by more than an accumulated 0.1 m, the canister may be damaged.
- Possible changes in groundwater flow and groundwater chemistry due to earthquakes.

The study of earthquake effects after closure is focussed on issues that may impair the isolation of the spent fuel; one of the most important is the possible effect of faulting. The canisters are positioned in "good" rock whereas "poor" rock such as fault zones are avoided due to potential future movements, high transmissivity, etc. The layout of the repository is such that a certain "respect distance" from a fault to the nearest canister is ensured Figure 1-4. Field observations of rock conditions close to displaced faults are important data for estimation of proper "respect distances"; the few cases observed in other countries, where tunnels cut faults that have slipped due to earthquakes, constitute important data and they are compiled in this report.

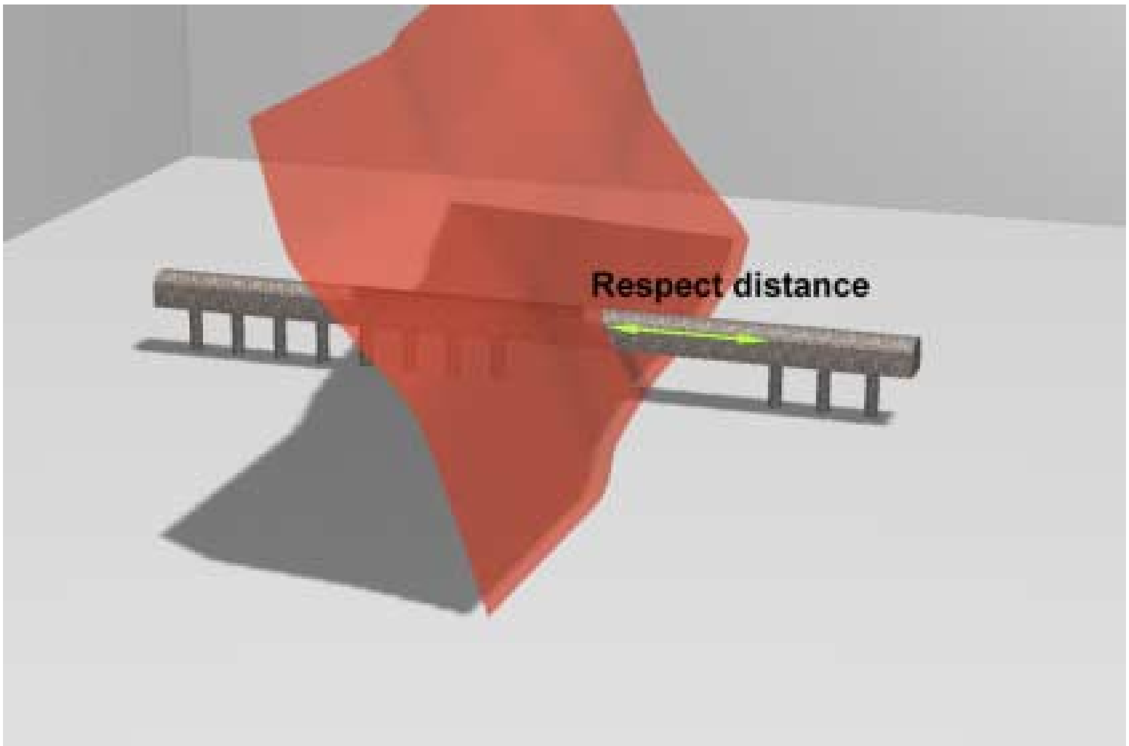


Figure 1-4. *The picture explains the concept of "respect distance". Spent fuel is not deposited close to fault where future re-activation may damage the rock. The respect distance to faults is site- and fault specific. In the most recent safety analysis, /SKB, 1999b/ assumed that the respect distance to fracture zones and faults is 100 m for structures bounding the repository area and 50 m to structures that are permitted within the repository area but not permitted to cut deposition tunnels.*

1.3 Earthquakes in Sweden relative to the world

Earthquakes occur when stresses in the earth reach a level greater than the strength of the weakest part of the rock, (often pre-existing planes of weakness) causing the rocks on opposite sides of a fault to suddenly and violently slip past one another. From a global perspective, the largest earthquakes occur where continental plates collide. Figure 1-5 illustrates that foremost, the global seismic hazard is along the Pacific Rim and in a belt from Greece-Turkey-Iran over to the Himalayas and down to Indonesia. As shown in the figure, Sweden is located in a low-hazard area.

Figure 1-6 illustrates a recent study on present Scandinavian seismicity. The anticipated Peak Ground Acceleration (PGA) is in the order of 0.01 g for most parts of Sweden where g is the acceleration due to gravity (~9.8 m/s^2). It will be shown later that underground damage rarely occurs for PGA < 0.2 g. Though the present seismicity is low in Sweden, there is evidence for increased seismicity associated to the latest deglaciation. Figure 1-1 depicts position and extent of known post-glacial fault scarps in Scandinavia. Since future glaciations and deglaciations are expected for the coming 100 000 years it is probable that similar events will occur during the time-period that the spent fuel still constitute a potential hazard.

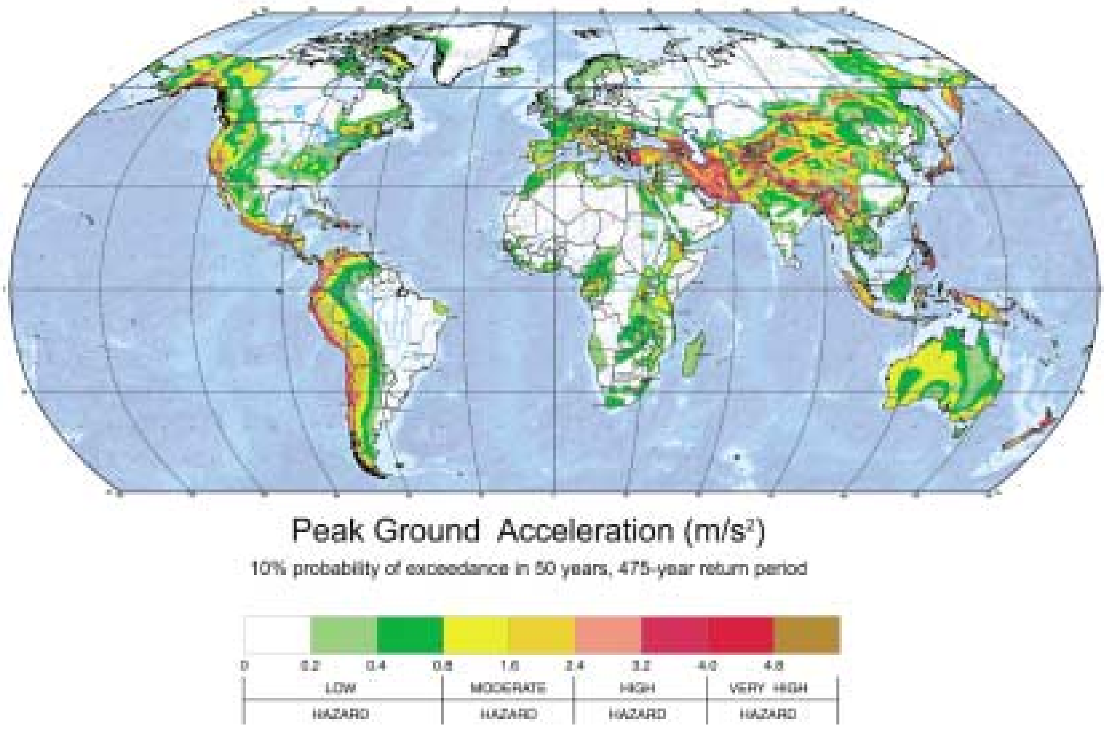


Figure 1-5. *Global Seismic Hazard Map produced by the Global Seismic Hazard Assessment Program. The program was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR). The GSHAP project was terminated in 1999. The picture reveals that red areas (high hazard) are connected to areas where the continental plates collide. The Baltic Shield is a low-hazardous area of the world /from GSHAP, 1999/. The colours depict 10% probability of exceedance of peak ground acceleration in 50 years, corresponding to a mean return period of 475 year. White areas: <0.2* m/s^2 *; Green: 0.2–0.8; Yellow: 0.8–2.4; Red > 2.4. It follows from this study that damages in tunnels due to earthquake shaking are limited to orange, or brown areas on the map.*

Deposition of spent fuel is planned to begin around year 2015. The repository is planned to be in regular operation around 40 years before it is permanently sealed off. Considering the seismic hazard illustrated in Figure 1-6, the repository may experience shaking due to a few, minor, earthquakes, but these are expected to be harmless at the surface and much more so underground. Possible effects of earthquakes will be much less important than e.g. at the interim storage of spent fuel, CLAB, or at the nuclear reactors themselves as the spent fuel is encapsulated in thick copper-steel canisters.

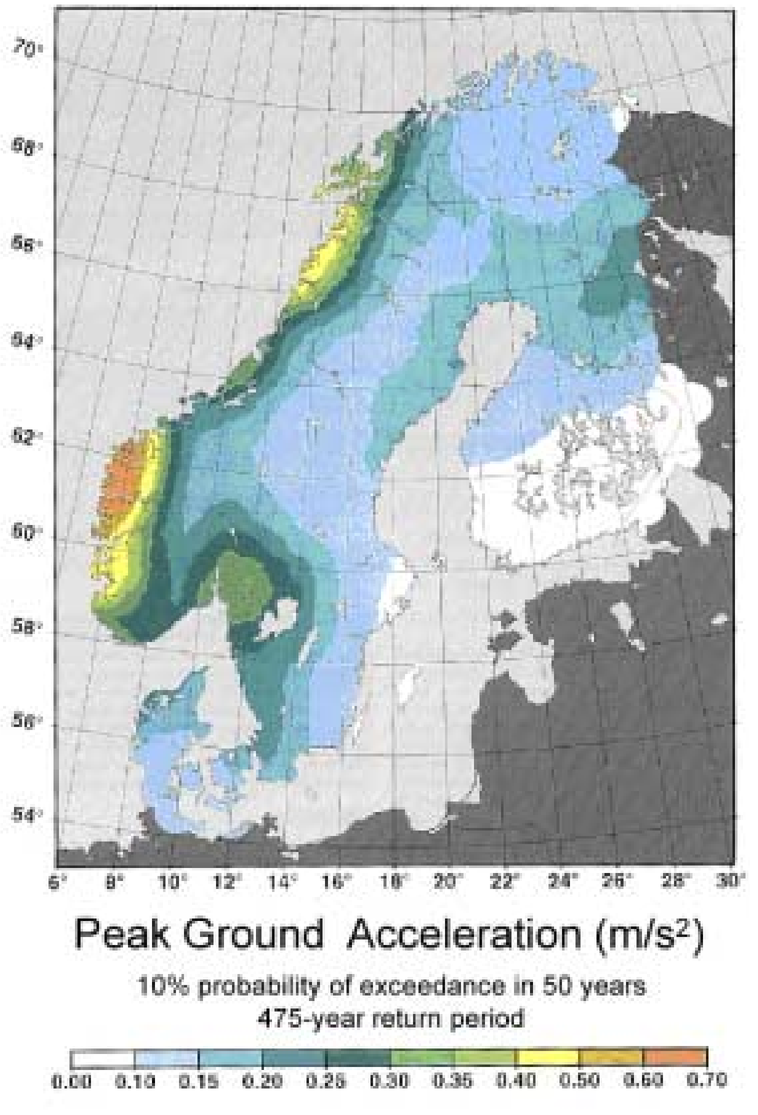


Figure 1-6. *The picture shows the 10% probability of exceedance of horizontal Peak Ground Acceleration (m/s^2) in 50 years /Wahlström and Grünthal, 2000a/. The major area in Sweden is light blue 0.10–0.15 m/s^2, i.e. 0.010–0.015 g where g is the acceleration due to gravity. Note that underground damage due to shaking empirically requires PGA > 0.2 g, at least 10 times more than anticipated for most areas in Sweden.*

1.4 Description of tunnel technology

Tunnels in Sweden are almost without exception excavated in hard rock. The tunnels are occasionally supported by rock bolts and shotcrete where the rock is of poor quality or where the function of the tunnel requires a higher degree of safety. The deposition tunnel for the deep repository (in case of vertical deposition) is planned to be constructed in good rock with no need for rock support. In this technical report, tunnel data stems from diverse geological environments, many of which may be characterised as various forms of soils. Figure 1-7 illustrates schematically common types of tunnels in the databases described in this report. Tunnels are in general lined with 0.2–0.5 m of concrete where tunnels are excavated in soft rock or where the use of the tunnel requires high safety and infrequent maintenance. Close to the surface, cut-and-cover tunnels are common. The soil or unconsolidated rock is removed and a concrete structure assembled before the pit is backfilled with the excavated material.

Figure 1-8 shows a lined tunnel constructed in unconsolidated sediments. The picture is shown as a typical background to the damage records to be presented later in this report. The geology shown is however not typical for Swedish geology and definitely not for the potential sites for a deep repository.

For the interested reader, the paper by /Asakura, 1998/ makes an exposé of the development of tunnelling from the ancient Greek civilisation to present technology, with emphasis on the progress of tunnelling in Japan.

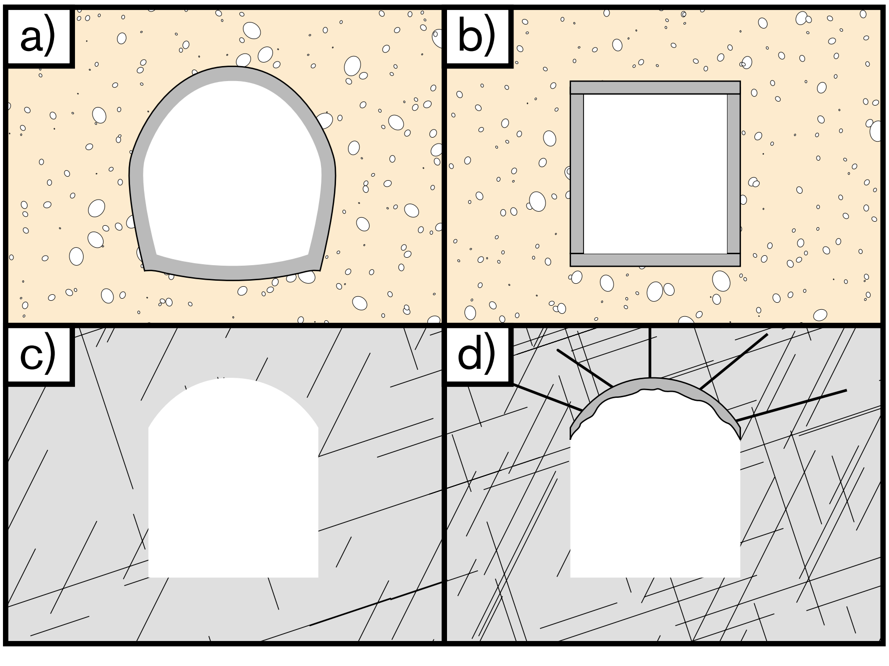


Figure 1-7. *Types of tunnels in this report a) tunnel lined with concrete b) cut-and-cover tunnel c) unlined tunnel d) unlined tunnel with rock bolts and shotcrete (concrete that is sprayed on the tunnel walls).*

Figure 1-8. *The Chi-Chi earthquake in Taiwan 21 September 1999 displaced the Shih-Gang Dam water conveyance tunnel intersecting the Chelungpu fault that ruptured the surface for ~100 km. This tunnel was sheared off 4 m vertically and 3 m horizontally. Damage in the tunnel lining was limited to within a few meters of the reactivated fault /Wang et al, 2001/. The Shih-Gang Dam water conveyance tunnel is around 10 m below surface and excavated through unconsolidated alluvium. The tunnel was excavated by a ripper and lined with concrete. Courtesy: Mr T T Wang.*

1.5 Description of this study

The project *Effects of Earthquakes on Underground Facilities* aims to recompile field evidence of seismic damage on underground facilities, to shed additional light on the matter of friction loss in bedrock due to water-level changes and finally to find suitable ways to inform concerned Swedish citizens on the matter. With respect to the safety-related issues (Chapter 1.2), the possibility of future reactivation of fractures with displacements > 0.1 m was given the highest priority in this study.

A fact-finding stage was initiated early year 2001 with interviews, literature surveys, searching the Internet and by sending circular letters asking for co-operation. The surveys revealed more than 150 published papers of relevance to the subject, c.f. Chapters 6 (References) and 7 (Bibliography). About 60 circular letters were sent to organisations and individuals in China, Iran, Japan, Russia, Taiwan and the USA, many of which contributed with information. A study-tour to Japan, South Africa and Taiwan, in the autumn of 2001, was carried out to collect supplementary information and to check preliminary results and conclusions based on the information at hand. Nine pertinent organisations were visited in Japan. The draft report was then peer reviewed by several experts in Japan, Taiwan and in Sweden.

At the onset of this study it was apparent that post-closure issues were the most important especially information to support estimation of "respect distance". In spite of this, effects of shakings on underground openings are included as these results are interesting for the very pessimistic assumption that the repository is not backfilled at all. One difficulty found when performing the study is that the classification of damage due to earthquake not always has been crisp and consistent in the published literature. Recent damage classification is however more functional and the classes of damage described more in detail than in the older literature.

During the course of the project we decided to include results of experiments and numerical models to provide additional perspective on the safety-related issues of the repository. A situation where future, large earthquakes will occur is in many ways anomalous to present-day geological conditions. In Chapter 4.7 it is argued that the data acquired from current earthquakes and its effects are relevant to find answers to the questions posed.

1.6 This report

The main purpose of the report is to provide an up-to-date reference of published effects of earthquakes on underground facilities. The report should be useful and understandable both for the expert and the concerned citizen wanting to be informed on issues relevant to the implementation of the deep repository for spent fuel in Sweden and elsewhere. SKB uses this report to check that Swedish assumptions used for site selection, repository design and methods to analyse the pre- and post-closure safety is consistent with the up-to-date information provided here.

Chapter 2 provides the general empirical background to earthquakes and damage to underground openings by the authors' compilation of previous compilations. It would be a practical impossibility to go back to each basic source for each damage records, written in a multitude of languages, generated over hundred of years. The cited compilations are made by distinguished researchers and their respective contribution have in most cases been published in peer reviewed scientific journals and thus constitute a good historical and scientific basis.

Chapter 3 is a countrywide overview of field-data. Published records from earthquakes and underground damage to openings in China, Italy, Japan, South Africa, Taiwan, USA and former Yugoslavia are reported. The relevant papers have been screened of information of relevance to the objectives of this study. The compilations in Chapter 2 were mostly concerned with effects of shaking and did not treat effects of faulting. In view of this, Chapter 3 is mostly concerned with the effect of faulting, as these effects are relevant for selecting the proper "respect distances" from a fracture or fracture zone to the deposited spent fuel.

Chapter 4 is devoted to the specific safety-related issues for the repository. The data from Chapter 2 and Chapter 3 are combined with progress results from theoretical analyses and physical and numerical models to provide statements on the issues as stated in Chapter 1.2.

Chapter 5 provides the overall conclusions of the study. References used in this report are included in the reference list (Chapter 6). Other publications that have been studied but not referred to are presented in the bibliography (Chapter 7). The Appendix includes many technical subjects, some for the expert reader, some for the laymen, c.f. Table of Contents.

The results of this study are open to the public and is intended to be presented in popularised versions to the Swedish audience. This report is also available for download at the SKB official web-site www.skb.se.

1.7 Where to find general information on earthquakes?

The non-expert reader may wish to obtain additional information. The Internet is an outstanding source of information. The following number of hits was recorded July 12th, 2001, respectively June 11th, 2002 (within parentheses) using the search engine www.google.com:

Earthquake	1 320 000 (1 680 000)
Earthquake + damage	224 000 (282 000)
Earthquake + damage + underground	26 400 (30 600)
Earthquake + damage + tunnel	10 900 (12 900)

The reader is recommended to visit web-sites for excellent general information on earthquakes. The sites in Table 1-1 are official sites and should provide reliable information in English.

Table 1-1. Sources for general information on earthquakes including Frequently Asked Questions (FAQ).

Organization	Web-site (As of June 10, 2002)	Special Feature
CNSS (Council of the National Seismic System)	http://quake.geo.berkeley.edu/cnss/catalog-search.html	Downloadable earthquake data
Earthquake Engineering Research Institute	www.eeri.org	Links
Earthquake Information Center, University of Tokyo	http://wwweic.eri.u-tokyo.ac.jp/index-e.html	Earthquake catalogues
Earthquake Information Network	www.eqnet.org	Links to several facts
Encyclopædia Brittanica	www.brittanica.com (search for earthquake)	Video animation of seismic waves
Incorporated Research Institutions for Seismology	www.iris.edu	General science portal
International Association of Seismology and Physics of the Earth's Interior	www.iaspei.org	Links
International Center for Disaster – Mitigation Engineering. Institute of Industrial Science, University of Tokyo	http://incede.iis.u-tokyo.ac.jp/index.htm	Focus on disasters and earthquakes in Japan
International Seismological Centre	www.isc.ak.uk	Bulletins
National Information Service for Earthquake Engineering University of California, Berkeley	http://nisee.berkeley.edu	~100 000 abstracts image database, links
Observatories and Research Facilities for European Seismology	http://orfeus.knmi.nl/	Links
US Geological Survey, Earthquake Hazards Program	http://quake.wr.usgs.gov/	Specialized on Northern California
Unites States Geological Survey	http://earthquake.usgs.gov	FAQ, glossary for kids
University of Washington	http://www.geophys.washington.edu/seismosurfing.html#global	Links
USGS National Earthquake Information Center	http://wwwneic.cr.usgs.gov/	Downloadable earthquake data

1.8 Acknowledgements

There are several organisations and individuals that in one way or another have contributed to the results of this project. Table 1-2 is intended to give the complete picture of active contributors to the project. Any eventual omission is unintentional. The authors are most grateful for the shown interest and received contributions. We hereby express our sincere gratitude.

Table 1-2. Contributors to the project.

Name	Country	Affiliation
Dor, O Rechez, Z	Israel	Hebrew University
Cotecchia, V Trizzino, R	Italy	University of Bari
Nishi, K Kawanishi, M	Japan	Central Research Institute of Electric Power Industry
Moro, Y	Japan	Hazama Corp
Aoki, K Ishikawa, H Sakuma, H	Japan	Japan Nuclear Cycle Development Institute
Yoshida, H	Japan	Nagoya University Museum
Kodama, K	Japan	National Institute for Industrial Science and Technology – Research Center for Deep Geological Environments
Mashimo, H	Japan	Public Works Research Institute
Kojima, K	Japan	Railway Technical Research Institute
Watanabe, K	Japan	Saitama University
Asakura, T Kobayashi, A	Japan	University of Kyoto
Konagai, K	Japan	University of Tokyo
Tanaka, K	Japan	Yamaguchi University
Durrheim, R	South Africa	CSIR Deepmine
Aswegen G van	South Africa	ISS International
Ebrahim-Trollope, S	South Africa	SiM Mining Consultant
Ortlepp, W D	South Africa	SRK Consulting
Hökmark, H	Sweden	Clay Technology
Lindblom, U	Sweden	Gecon
Pusch, R	Sweden	Geodevelopment
Bodare, A	Sweden	Royal Institute of Technology
Christiansson, R Hörnfeldt, B	Sweden	Swedish Nuclear Fuel and Waste Management Co
Arvidsson, R	Sweden	Uppsala University
Lee C-T	Taiwan	National Central University
Wang, T T	Taiwan	National Taiwan University
Ouyang, S	Taiwan	Industrial Technology Research Institute
Allen, C A	USA	California Inst of Technology
Tubbesing, S	USA	Earthquake Engineering Research Institute
King, C-Y	USA	Earthquake Prediction Research Inc
Sharma, S	USA	University of Idaho
Levich, R Savino, J Sullivan, T	USA	US Department of Energy, Yucca Mouintain Project

2 Published compilations of earthquake influence on underground facilities

This Chapter mainly presents previous compilations of damage on underground facilities due to earthquakes. The intention is to present a general empirical background and to extract information of relevance for this particular study. The following compilations were found to be of special value for this project:

- /Asakura and Sato, 1998/
- /Carpenter and Chung, 1986/
- /Dowding and Rozen, 1978/
- /Duke and Leeds, 1959/
- /Owen and Scholl, 1980/
- /Power et al, 1998/
- /Pratt et al, 1980/
- /Stevens, 1977/
- /Yoshikawa and Fukuchi, 1984/

Table 2-1 extracts information provided in all these previous compilations.

Table 2-1. Overview of results presented in earlier compilations and studies.

Compilation Ref	Main events	Main references	Main issues studied	Main conclusions
/Dowding and Rozen, 1978/	71 cases from California, Alaska and Japan. San Fransisco (1906), Kanto (1923), Kern (1952), Niigata (1964), Alaska (1964), San Fernando (1971)	/Rozen, 1976/	Rock tunnel damage due to shaking. Comparison of damage resulting from underground explosion tests. Observed modes of tunnel damage.	Tunnels are much safer than aboveground structures for a given intensity of shaking. Tunnels in soft soil or rock, which suffer from instability during construction, are more susceptible to damage during earthquakes. Deep tunnels are safer than shallow tunnels. Total collapse was only found associated to movement of an intersecting fault. No damage in lined or unlined tunnels at surface accelerations up to 0.19 g.
/Pratt et al, 1980/		/Duke and Leeds, 1959; NRC, 1964a,b; Rozen, 1976/	Review of existing database for tunnels, shallow underground openings, mines and other deep structures. Review of measurements of attenuation. Nuclear events as earthquake simulators. Displacement as a function of depth. Analytical models to predict displacement as a function of distance and orientation from a given source.	Very few data on earthquake damage in the subsurface. More damage in shallow, near-surface tunnels than in deep mines, particularly sparse data below 500m. Large displacements occur primarily along pre-existing faults and fractures and at the surface entrance to the facilities. Vertical structures as shafts and wells are not as susceptible to damage as surface facilities. Less effects in consolidated than unconsolidated rock. Frequencies most likely to damage sub-surface openings are significantly higher (50–100 Hz) than the frequencies (2–10 Hz) that cause damage to surface facilities. Most block motion displacements recorded at the surface or at the free surface of tunnels.

Compilation Ref	Main events	Main references	Main issues studied	Main conclusions
/McClure and Cole, 1981/	107 cases from Chile, China, India, Italy, Japan, Mexico, Portugal, USA from the years 1755–1980 c.f. Table 1 in the reference e.g. Lisbon (1755), Atacama (1922), Kern County (1952), Kita-Mino (1961), Koyna (1967), San Fernando (1971), Tang-Shan (1976)	/Dowding and Rozen, 1978; Duke and Leeds, 1959; Pratt et al, 1980; Rozen, 1976; Stevens, 1977/	Damage due to shaking in rock.	Underground structures in rock suffer very little damage due to earthquake shaking. Ratio of surface to underground seismic wave amplitudes depends on the type of ground and is greater for alluvium than for hard rocks; attenuation with depth is in the order 1.1 to 1.7 in rock. Damage estimation based on data from nuclear explosions is uncertain. For safety purpose: facilities underground should be sited in rock where the shear wave velocity is greater than 900 m/s. The facility should be deeper than 90m. The facility should not be located in the immediate vicinity of active or potentially active faults. Particle velocity useful measure to evaluate earthquake threshold criteria.
/Brown et al, 1981/	Case histories from California, Japan. San Francisco (1906), Kita-Izu (1930), Kern (1952), San Fernando (1971), Izu-Oshima-Kinkai (1978)	/Dowding and Rozen, 1978; Owen and Scholl, 1980/, several Japanese references	The response of the Bay Area Rapid Transit twin tunnels (San Francisco) to slow lateral slippage at the Hayward Fault. Case histories focus on cases where slip data have been collected.	The BART tunnels through Berkeley Hills have been displaced around 80 mm right laterally over a period of 12 years. This has occurred over a short section at the slipping Hayward Fault.

Compilation Ref	Main events	Main references	Main issues studied	Main conclusions
/Murano and Takewaki, 1984/	Kanto (1923), Kita-Mino (1961), Izu-Oshíma-Kinkai (1978)	/Onoda et al, 1978/ and several Japanese sources	Earthquake damage to tunnels and underground powerhouses. Rock and rock caverns in Japan. Analytical studies.	Tunnel portal is more susceptible to earthquakes than the tunnel. Damage is closely related to the properties of the rock surrounding the tunnel and the lining thickness. The more inferior the properties of the rock are, the greater the damage becomes if the lining is thick. When tunnel lining is cracking – longitudinal and transverse cracks of the arch are most common. Active faults (i.e. faults that have shown repeated activitations during the Quaternary) should – if possible – not be cut by a tunnel, as it is possible that the fault may move during the earthquake. Earthquake motions are amplified in weathered zones. Acceleration at the portal is twice as high as in the tunnel. The axial strain at the tunnel crossing are around 10 times higher than at the other portions. The circumferential strain at the crown is greater than the axial strain. Acceleration (Shiroyama power plant) has predominant frequencies 3–6 Hz and the measured dynamic strain in the cavern predominates at 0.1 Hz. Acceleration tends to be slightly amplified in underground powerhouses.
/Yoshikawa and Fukuchi, 1984/	124 cases of damage from earthquakes in Japan. Kanto (1923), Kitaizu (1930), Fukui (1948), Niigata (1964), Izu-Oshima-Kinkai (1978)	/Yoshikawa, 1979, 1981/	Analysis of causes of damage, e.g. unstable slopes, past deformation, poor geology, disaster during construction, action of fault.	Study the background to damage when analysing earthquake damage. Of 53 cases of heavy damage, 44 cases (83%) were influenced by "potential backgrounds", i.e. 25 connected to slope failures, 5 to past deformation history, 8 to poor geology, 2 to damage during previous construction, 2 to poor lining and 2 to action of faults.

Compilation Ref	Main events	Main references	Main issues studied	Main conclusions
/Loofbourow, 1985/	California – San Francisco (1906), Imperial Valley (1915), Santa Barbara (1925), Long Beach (1933), El Centro (1940), Arvin (1952), Western Nevada (1954), San Fernando (1971), Chile – (1924, 1927, 1928,1938, 1965, 1971), Japan – (1923, 1930), Greece Ancient underground constructions	/Duke and Leeds, 1959; Sandström, 1963/ and several references from personal contact with researchers and companies worldwide	Effects on tunnels, powerhouses, mine workings and oil wells in a number of seismically active areas as a means of evaluating seismic damage of existing and future underground developments in Kansas City, Missouri area.	Conducive factors to seismic damage are: Active faults – seismic risks in California, Japan, Chile, and Peru. Foundations on thick alluvium – Manila, Tokyo, New Madrid. Portals in weak or decomposed rock and tunnels under shallow cover of similar material – Japan. Extremely rugged terrain – Alps, Peru, Chile. Avalanches of snow, ice, loose rock – the Alps, Peru, Chile, China. Movement of a huge volume of soil – along the Mississippi River, below Cairo. Foundations on thixotropic clay, acting as liquid when saturated and shaken – Anchorage, Alaska. Strong rock already very highly stressed, e.g. in rock bursts in some very deep mines – South Africa. Conditions at Kansas City are safe with respect to underground construction.
/Carpenter and Chung, 1986/	Several (not described in detail) + nuclear explosions	Papers published 1958–1985, /Marine, 1981; Moran and Duke, 1975; Sandström, 1963; Stevens, 1977; Yoshikawa, 1979, 1981; Youd and Hoose, 1978/	Literature surveys on ground motion of interest for nuclear waste management.	Damage to be expected if fault displacement occurs through a site. Amplitude reduction with depth. Frequency content is important with respect to stability of underground openings. Model studies indicate problems for shafts and in-shaft-waste-handling equipment. Closer relationship peak velocity – damage than between peak acceleration and damage.

Compilation Ref	Main events	Main references	Main issues studied	Main conclusions
/Röshoff, 1989/	Several, mainly USA, Japan, China and the Soviet Union	/Carpenter and Chung, 1986; Dowding, 1979; Dowding and Rozen, 1978; Duke and Leeds, 1959; McClure and Cole, 1981; Murano and Takewaki, 1984; Pratt et al, 1980; Stevens, 1977/	Damage effects by earthquakes and changes in ground water levels, pressure, flow and chemistry in ground water and soil gases.	Generally low impact on underground facilities. Deeply located facilities more stable. Groundwater inflow to an underground opening may increase or decrease as an effect of an earthquake. Concentration or gases may increase or decrease prior to seismic events.
/Sharma and Judd, 1991/	192 reports from behaviour at 85 earthquakes world-wide	/Dowding and Rozen, 1978; Duke and Leeds, 1959; McClure and Cole, 1981; Owen and Scholl, 1980; Pratt et al, 1982; Rozen, 1976; Sharma, 1989; Stevens, 1977/, (156 cases), literature survey (+36 cases)	Important factors that affect underground damage.	94 cases of damage were found with decreasing damage with overburden depth. Damage related to Peak Ground Acceleration based on magnitude and epicentral distance. Less damage in competent rock. Non-conclusive with respect to type of support.
/Kana et al, 1991/		223 references and 346 references added as bibliography	Literature review to determine the nature and scope of technical information available to characterise the seismic performance of an underground repository and associated facilities – the Yucca Mountain Project.	Conventional practices for mine design and construction will provide stable underground excavations. Necessary design requirements more stringent than in established practice. Peak Ground Acceleration or velocity is not a scientifically sound method to determine prospective seismic effects.
/Doe, 1997/	Hayward Fault	/Brown et al, 1981/	Examples of tunnel design and performance through faults in California and Japan and from mines in South Africa.	In general, design has not been made to accommodate fault displacements in the past. Recently design accommodates fault displacements by increasing the flexibility of the lining; also flexible joints are used.

Compilation Ref	Main events	Main references	Main issues studied	Main conclusions
/Asakura and Sato, 1998/	Kanto (1923), Kita-Tango (1927), Kita-Izu (1930), Fukui (1948), Tokachi-oki (1952), Kita-Mino (1961), Niigata (1964), Tokachi-oki (1968), Izu-Oshima-kinkai (1978), Miyagiken-oki (1978), Urakawa-oki (1982), Nihonkai-chubu (1983), Naganoken-seibu (1984), Chibaken-toho-oki (1987), Notohanto-oki (1993), Hokkaido-nansei-oki (1993), Hyogoken-Nanbu (1995)	/Yoshikawa, 1981/	Review of effect of the Hyogoken-Nanbu (Kobe 1995) earthquake on 100 mountain tunnels. Review of effects of earthquakes in the past is included in the paper. Three evidences of earthquake fault crossing causing damage; the 1930 Kita-Izu, the 1978 Izu-Oshima-Kinkai and the 1984 Naganoken-Seibu earthquakes.	Less influence sub-surface than at surface. Ten tunnels suffered remarkable damage needing repair and reinforcement. 20–30 tunnels were influenced. Large part of damage locations coincided with locations of existing faults and fracture zones that had been recognized during construction. Mountain tunnels in sound rock and lined without material and structural defects are less affected by an earthquake even if it is very large. Mountain tunnels may suffer some damage if the tunnel is located near the epicentre of the earthquake fault, i.e. within 10 km for a magnitude 7 earthquake and 30 km for a magnitude 8 earthquake. Damage may also occur when the tunnel has special geological or construction conditions, such as slope stability around tunnel portal, crossing the existing faults or fracture zones, collapse or water inflow trouble during construction etc.
/Power et al, 1998/	Removal-reanalyses and addition of previous compilations resulting in 204 observations from moderate-to large events. 97 of the cases are from the Hyogoken-Nanbu (1995) earthquake, 31 from the 1994 Northridge quake and 21 from the 1989 Loma Prieta earthquake.	/Dowding and Rozen, 1978; Duke and Leeds, 1959; Owen and Scholl, 1980; Sharma and Judd, 1991/	Re-evaluation of existing seismic damage criteria using data from bored tunnels only. Focus on damage due to shaking. Aseismic design of tunnel design.	PGA ≤ 0.2 g; Ground shaking caused very little damage (minor cracking and spalling). 0.2 g < PGA ≤ 0.6 g; Instances of slight to heavy damage PGA > 0.6 g; a number of instances where damage is slight to moderate (major cracking, spalling). Tunnels having stronger lining system appeared to have performed better, especially reinforced concrete and/or steel linings. N.B. Heavy damage is all from the Kanto 1923 quake where damage might be due to landslide and the tunnel being shallow at parts. Bored tunnels seem to be more stable at an earthquake.
/Raney, 1988/				Note: It has not been possible to find a copy of this reference.

The following three important papers by /Dowding and Rozen, 1978/, by /Sharma and Judd, 1991/, and /Asakura et al, 1998/ will be further expanded.

/Dowding and Rozen, 1978/ is one of the most cited references concerning earthquake effects on tunnels. They studied 71 cases to determine damage modes. The investigation was focussed on damage due to shaking and 42 damages, ranging from cracking to closure of openings, were recorded. Peak ground acceleration was compared to damage (see Figure 2-1 for basic notations).

The tunnels in the database were mainly 3–6 m in diameter. Unfortunately it was only possible to find detailed, geological information on 23 out of the 71 cases. The tunnels were constructed from the late 1800'ies to the present and they represent a wide variety of construction and tunnelling methods. The 71 cases involved earthquakes with Richter magnitude 5.8–8.3 and focal depths in the range 13–40 km. /Dowding and Rozen, 1978/ concluded that there were not even one report on falling stones in unlined tunnels, or cracking in lined tunnels, up to 0.19 g and only a few incidents of concrete cracking in lined tunnels for up to 0.25 g. Between 0.25 g and 0.52 g, there was only one partial collapse due to landsliding, Figure 2-2. The corresponding damaging velocities were 200 mm/s, 400 mm/s and 800 mm/s respectively.

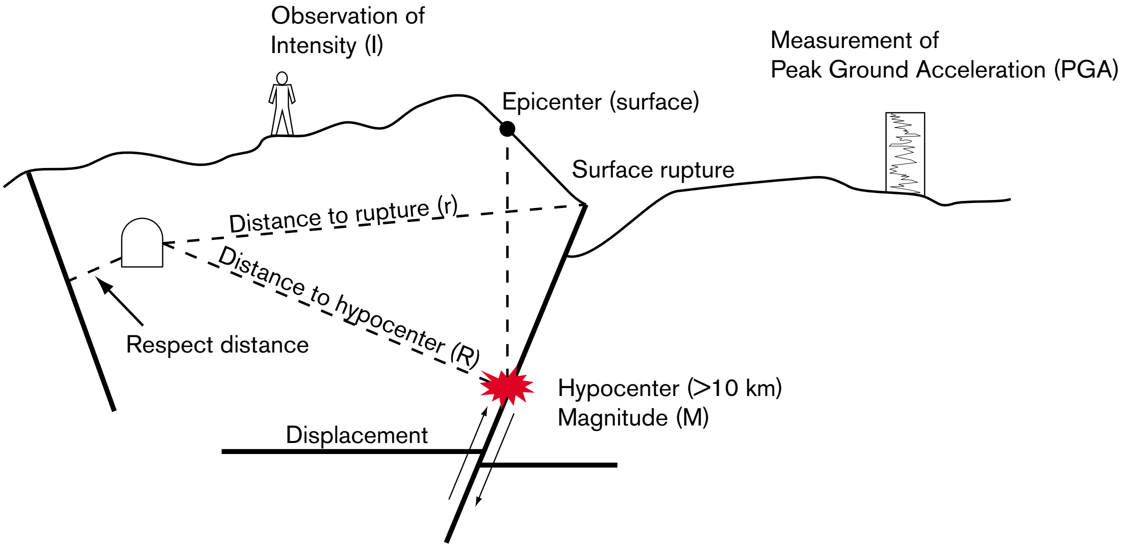


Figure 2-1. The studies of earthquake damage are often performed in the following way: Observation of Intensity I or Magnitude M is recorded. The distance to the tunnel is determined. The distance is either the distance to the hypocenter (R) or in recent science the distance from the surface fault to the tunnel (r). The Peak Ground Acceleration (PGA) at the surface attenuates as a function of magnitude and distance. /Dowding and Rozen, 1978/ calculated the attenuation accordingly to the work of /McGuire, 1974/. The PGA is compared to tunnel damage. The tunnel damage can either be functional (level of loss of function) or classified according to damage to the tunnel and/or the rock support.

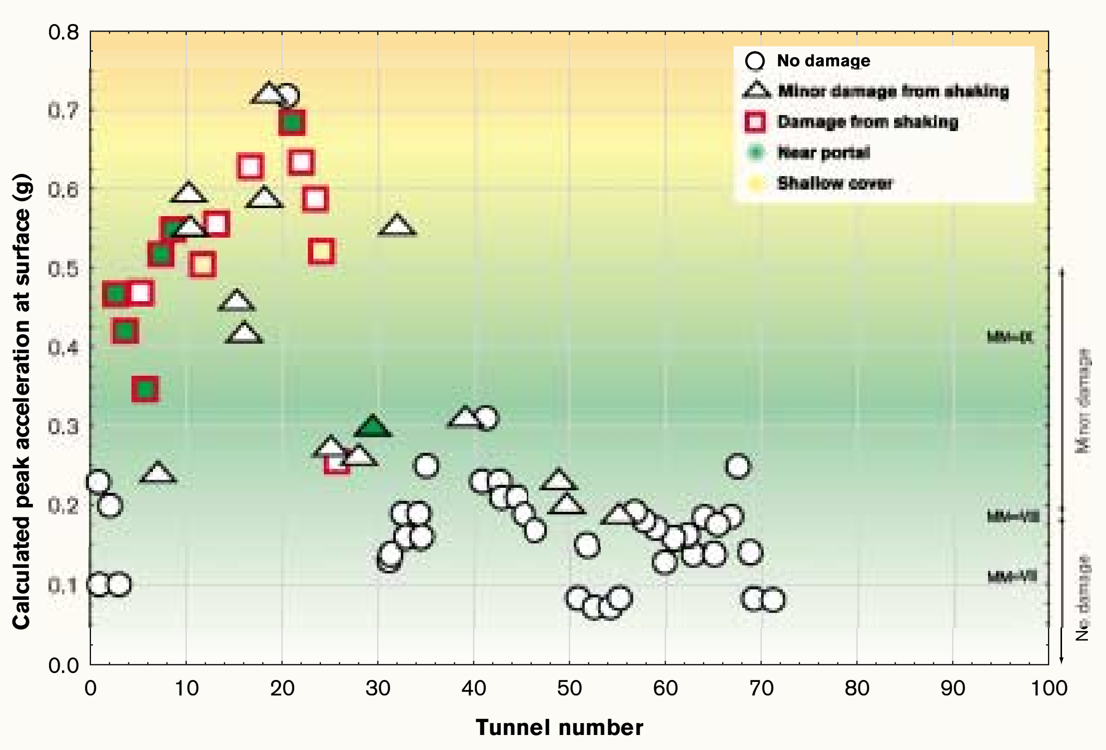


Figure 2-2. The magnitudes have been converted to Peak Ground Acceleration at surface (% of gravitational acceleration g) using the /McGuire, 1974/-relation between magnitude, distance and acceleration. No damage is known for PGA < 0.2 g corresponding to intensity VIII on the MM-scale (see Appendix A). Minor damage due to shaking implies fall of stones and formation of new fractures due to shaking. Damage (major rock falls, severe cracking and closure of opening) was predominantly at the tunnel portals /Revised after Dowding and Rozen, 1978/.

Many of the observed cracks on concrete linings may be due to pre-existing cracks due to shrinkage after construction, /Dowding, 1979/. Figure 2-3 summarises two relationships involving tunnel damage. The damages are compared to a) the Modified-Mercalli (MM) Intensity Levels for above-ground structures and b) to magnitude and distance. It is clear that peak surface acceleration that is expected to cause heavy damage at the surface (MM VIII–IX) only cause minor damage to tunnels.

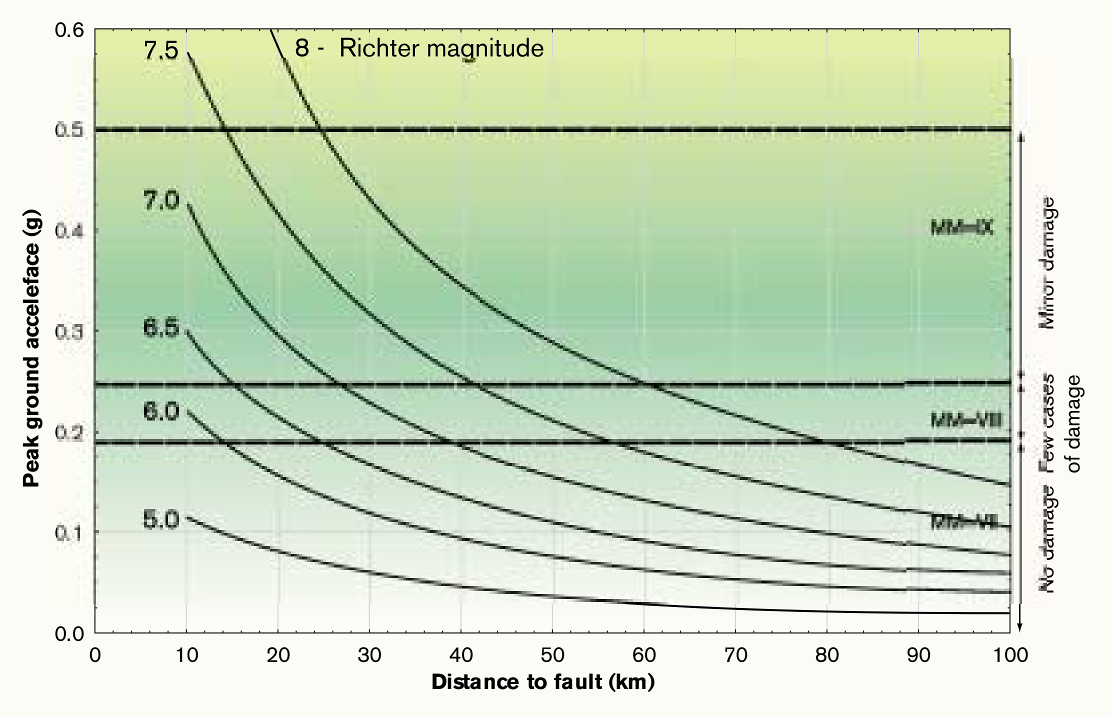


Figure 2-3. *Estimated damage due to shaking correlated to magnitude and distance. The damages are compared to the Modified-Mercalli (MM) Intensity Levels for above-ground structures. Secondly, the damage-level is correlated to magnitude and distance. It is clear that peak surface acceleration that is expected to cause heavy damage at the surface (MM VIII–IX) only cause minor damages to tunnels /Revised after Dowding and Rozen, 1978/.*

The paper of /Dowding and Rozen, 1978/ is a good starting-point for empirical knowledge as well as the work by /Sharma and Judd, 1991/. The latter reference is useful as the paper also summarises several previous compilations. A database was developed that includes the following features:

- 192 reports from 85 earthquakes considerably extending the databases by the following references: /Dowding and Rozen, 1978; Duke and Leeds, 1959; McClure and Cole, 1981; Owen and Scholl, 1980; Pratt et al, 1982; Rozen, 1976; Stevens, 1977/.
- Data (where available) on types and amount of overburden cover, rock-type and form of tunnel support, cause of damage (shaking, faults intersecting the opening, both from shaking and faulting). Note that damages on access portals were excluded from the study.

Where no measurements were available, magnitudes were calculated based on records on the intensity at the epicentral area as:

$$\mathbf{M} = 1 + \frac{2}{3} \cdot \mathbf{I}_0 \qquad 2\text{-}1$$

where I_O is the Modified-Mercalli Intensity in the epicentral area.

It was not possible for Sharma and Judd to compile complete data records for all events. The completeness of data base records is shown in the Table 2-2. A replica of the original database for the /Sharma and Judd, 1991/ work was kindly made available through the courtesy of Prof. Sunil Sharma, Univ. of Idaho. Table 2-3 shows the effect of overburden depth on the damage recorded.

The damage classification is not exactly described in the paper of Sharma and Judd but is assumed to be in accordance with the descriptions of /Dowding and Rozen, 1978/. However, it is noted that the frequency of damage reports decrease with depth, which is attributed to the lack of surface waves, lower acceleration with depth and increased strength of the rock with depth. Certainly, far more facilities exist at shallower depth a fact that may induce considerable bias. Table 2-3 is illustrated in Figure 2-4. Note that there are only five cases reported for moderate or heavy damage at levels below 300m (except a mine rockburst at 3000 m depth that is not included in Table 2-3).

Table 2-2. Overview of completeness of data base records /Based on Sharma and Judd, 1991/.

Number of reports	Number of data on depth (%, # of cases)	Number of data on rock type (%, # of cases)	Number of data on form of support (%, # of cases)	Number of data on geographic location (%, # of cases)
192 cases	69%, 132 cases	78%, 149 cases	83%, 159 cases	91%, 174 cases

Table 2-3. Effect of overburden depth (m) to damage in underground openings /After Sharma and Judd, 1991/.

Depth (m)	Extent of damage Heavy	Moderate	Slight	No damage
< 50	10	9	14	24
50 – < 100	2	1	2	12
100 – < 200	1	0	3	6
200 – < 300	1	2	3	13
300 – < 500	0	3	4	4
500 – < 1000	0	1	9	2
1000 – < 1500	0	1	0	4
Unknown	7	6	14	33
Total	**21**	**23**	**49**	**98**

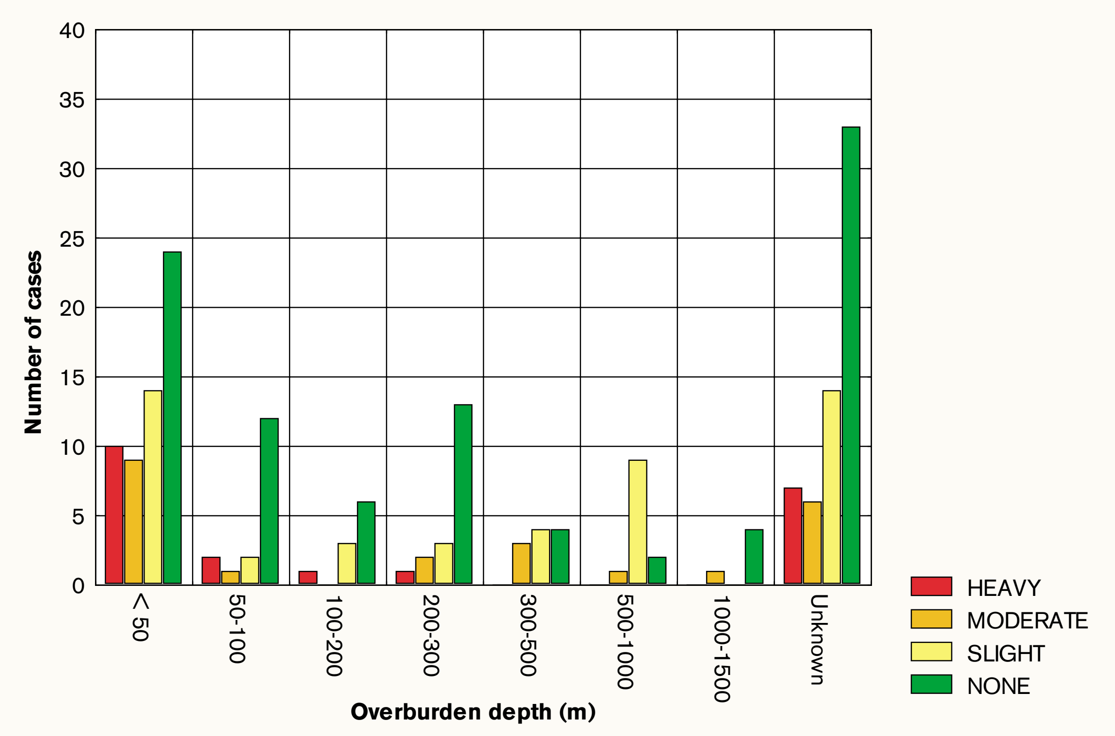


Figure 2-4. Effects of overburden depth on damage. No heavy damage is recorded at levels below 300 m, except for rockburst in a deep mine /Revised after Sharma and Judd, 1991/.

The damage as a function of rock type is illustrated in Table 2-4 and Figure 2-5. The denomination "Unknown" is probably hard rock. The colluvium is unconsolidated material deposited by water, gravity or wind.

Table 2-4. Damage in underground openings for different rock types /After Sharma and Judd, 1991/.

Depth (m)	Extent of damage Heavy	Moderate	Slight	No damage
Rock (?)	1	5	9	35
Sediment	4	6	19	11
Igneous	7	3	5	21
Metamorphous	1	0	0	8
Colluvium	3	4	4	3
Unknown	6	5	12	20
Total	**22**	**23**	**49**	**98**

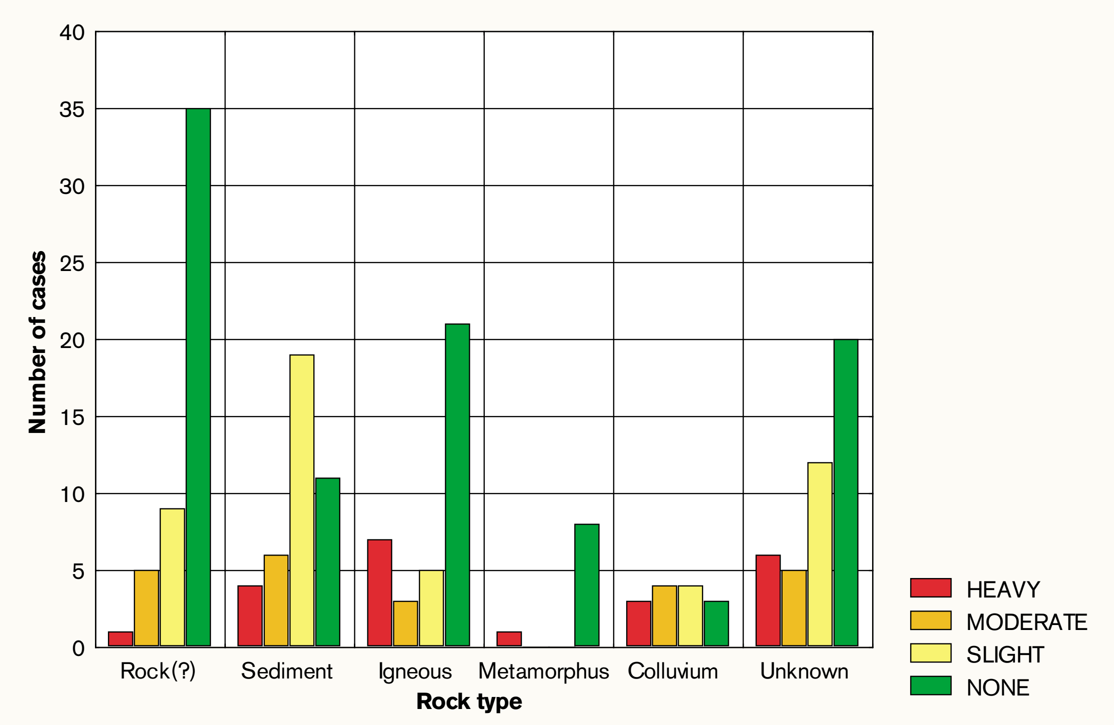


Figure 2-5. *Effects of rock type on damage /Revised after Sharma and Judd, 1991/.*

Of the reports on openings, 73% of openings in sedimentary rocks had suffered damage the figure being 79% in colluvial materials. The reports on damage in igneous rocks were down to 42%. Table 2-5 shows an extraction from the database. Records show the cases at depth where the rock is igneous or unknown and where faulting causes damage.

Of the nine cases extracted, five were events in mines where the stress situation can be quite different from that in an ordinary civil engineering situation. Cases where tunnels were damaged in igneous rock at an overburden depth ≥ 300 m are very unusual. Cases reported on damage associated to faulting are:

- the Tanna tunnel, Japan, (where the rock was very poor, c.f. Chapter 3.3.1),
- the Whittier tunnel, Alaska affected by the enormous Alaskan earthquake where slight damage to the timbered tunnel was found,
- the slight damage to the Koyna power station in India and finally,
- the Helms project tunnel in California where occasional rock falls occurred in the tunnel under construction when the earthquake hit /McClure and Cole, 1981/.

Table 2-5. Extract of the /Sharma and Judd, 1991/ database.

Site	Tombstone Mine, Arizona, USA	Tanna Tunnel, Japan	Morning Mine, Idaho, USA	Whittier RR Tunnel #1, Alaska, USA	Koyna Power Station, India	Zinc Mine, Tennessee, USA	Lai Luan Coal Mines, China	ERP Gold Mine, South Africa	Helms Project Tunnel, California, USA
Reference	/Owen and Scholl, 1980/	/Owen and Scholl, 1980/	/Owen and Scholl, 1980/	/Owen and Scholl, 1980/	/Okamoto and Tamura, 1973/	/Owen and Scholl, 1980/	/Owen and Scholl, 1980/	/McGarr, 1993/	/McClure and Cole, 1981/
Earthquake	Sonora	Kita Izu	N. Idaho	Great Alaskan	Koyna	Tennessee	Tangshan	EPRM	Fresno
Place	Mexico	Japan	USA	USA	India	USA	China	South Africa	California
Date	18870503	19301126	19440509	19640327	19671210	19690713	19760728	19780421	19800525
Magnitude	7	7.1	5	8.3	7	3.5	7.8	3.7	6.1
Epicentral Distance (km)	130	15	25	70	3	80	15	1	60
Rock type	?	Igneous	?	?	Igneous	?	?	Igneous	Igneous
Overburden (m)	183	150	1360	400	150	305	700	3000	250
Damage type	Shaking, Faulting	Faulting	Shaking, Faulting	Shaking, Faulting	Shaking, Faulting	Shaking, Faulting	Shaking, Faulting	Shaking, Faulting	Shaking, Faulting
Damage Level	Slight	Slight	Moderate	Slight	Slight	Slight	Moderate	Heavy	Slight
Rock Support Type	Unlined	Reinforced concrete lining	Unlined	Timber	?	Unlined	Unlined	Unlined	Unlined

The paper of /Asakura and Sato, 1998/ provides an excellent compilation of past earthquake damage to Japanese tunnels and also a description of damage due to the 1995 Hyogoken-Nanbu (Kobe) earthquake. Here we concentrate on the recent experiences, c.f. Table 2-6. They reported the following findings concerning past earthquakes:

- Less influence sub-surface than at surface.
- Large part of damage locations coincided with locations of existing faults and fracture zones that had been identified during construction.
- Mountain tunnels in sound rock and lined without material and structural defects are less affected by an earthquake even if it is very large.
- Mountain tunnels may suffer some damage if the tunnel is located near the epicentre of the earthquake fault, i.e. within 10 km for a magnitude 7 earthquake and 30 km for a magnitude 8 earthquake or, when the tunnel has special geological or construction conditions, such as poor slope stability around tunnel portal, crossing existing faults or fracture zones, or if collapse or water inflow trouble occurred during construction.

The information relating to more recent Japanese information is discussed further in Chapter 3.3.

/Power et al, 1998/ revisited the /Sharma and Judd, 1991/ database. They removed data for poorly documented earthquakes and data due to fault displacements, liquefaction and landsliding to concentrate on shaking-induced damage. Cut-and cover tunnels were removed from the database. Magnitudes were re-evaluated to moment magnitudes (M_w) and distances from tunnel to earthquake were taken as the closest distance to fault rupture surfaces. Peak ground acceleration at the ground surface was estimated based on recent attenuation relationships for ground (rock) motion. For each case, ground support was recorded (Unlined, Timber or Masonry, Concrete, Reinforced concrete or steel pipe). 97 of the 204 cases are from the Hyogoken-Nanbu (Kobe) earthquake, 31 from the 1994 Northridge quake and 22 from the 1989 Loma Prieta earthquake (c.f. Section 3.8). The conclusions from the study more or less confirm the conclusions by /Sharma and Judd, 1991/, which is evident by comparing Table 2-1, Figure 2-3 and Figure 2-6.

In summary: Worldwide, there are thousands of kilometres of tunnels, thousands of caverns, power stations and other underground facilities located in areas with frequent, very large earthquakes. The number of damage reports for these underground openings is, however, extremely low as compared to the rather frequent disasters reported for major damage at the surface of the earth in the same areas.

Table 2-6. Historical earthquake damages to Japanese tunnels year 1923–1993 /expanded after Asakura and Sato, 1998/.

Year Name	Magnitude	Epicenter	Depth* (km)	Area Most Affected (JMA – Intensity, c.f. Appendix A, Table A-2)	Tunnel Performance
1923 Kanto	7.9	Sagami Bay	? (10)	Kanagawa and Tokyo (VI)	Extensive, severest damage to more than 100 tunnels in southern Kanto area. Causes: Earthquake fault crossing, slope failure and mud-and-debris flow.
1927 Kita-Tango	7.3	7km WNW of Miyazu. Kyoto	0	Joint section of Tango Peninsula (VI)	Very slight damage to two railway tunnels in the epicentral region.
1930 Kita-Izu	7.3	7 km west of Atami. Shizuoka	0 (11)	Northern part of Izu Peninsula (VI)	Very severe damage to one railway tunnel due to earthquake fault crossing.
1948 Fukui	7.1	12 km north of Fukui city	0 (20)	Fukui Plain (VI)	Severe damage to two railway tunnels within 8 km from the earthquake fault.
1952 Tokachi-oki	8.2	Pacific Ocean, 73 km ESE off the Cape Erimo	0 (45)	Southern part of Hokkaido (VI–V)	Slight damage to 10 railway tunnels in Hokkaido. Causes: Long-time deteriorated tunnel lining.
1961 Kita-Mino	7	Near the border between Fukui and Gifu Prefectures	0 (25)	Vicinity of the Prefecture border (IV)	Cracking damage to a couple of aqueduct tunnels.
1964 Niigata	7.5	Japan Sea. 50 km NNE of Niigata City	40 (40)	Niigata City (V–VI)	Extensive damage to about 20 railway tunnels and one road tunnel. Causes: Poor geological conditions resulting in lining damage, constant landslide or unbalanced earth pressure.
1968 Tokachi-Oki	7.9	Pacific Ocean. 140 km SSE off the Cape Erimo	0	Aomori Prefecture (V)	Slight damage to 23 railway tunnels in Hokkaido. Causes: Constant landslide or unbalanced earth pressure, long-time deteriorated tunnel lining.
1978 Izu-Oshima-Kinkai	7	In the sea between Oshima Island and Inatori, Shizuoka	0 (23)	South-eastern Izu Peninsula (V–VI)	Very severe damage to 9 railway and 4 road tunnels in a limited area. Causes: Earthquake fault crossing, zones of poor geological conditions causing lining damage, a boulder or large-scale rock directly hit the portal.

Year Name	Magnitude	Epicenter	Depth* (km)	Area Most Affected (JMA – Intensity, c.f. Appendix A, Table A-2)	Tunnel Performance
1978 Miyagiken-oki	7.4	Pacific Ocean 112 km east of Sendai City	40 (44)	Sendai City and vicinity (V)	Slight damage to 6 railway tunnels mainly existing in Miyagi Prefecture
1982 Urakawa-oki	7.1	Pacific Ocean. 18 km SW of Urakawa. Hokkaido	40	Urakawa-Cho and Shizunai-Cho (IV–V)	Slight damage to 6 railway tunnels near Urakawa.
1983 Nihonkai-chubu	7.7	Japan Sea. 90 km west of Noshiro City. Akita	14	Noshiro City and Oga City, Akita (V)	Slight damage to 8 railway tunnels in Akita etc.
1984 Naganoken-seibu	6.8	9 km SE of Mt. Ontake, Nagano	2	Otaki Village, Nagano (VI–V)	Cracking damage to one headrace tunnel. Causes: Earthquake fault crossing
1987 Chibaken-toho-oki	6.7	Pacific Ocean. 8 km east off Ichinomiyacho, Chiba	58	Chiba Prefecture (V)	Damage to the wall of one railway tunnel at Kanagawa-Yamanashi border.
1993 Notohanto-oki	6.6	Japan Sea. 24 km north of Suzu City, Ishikawa	25	Suzu City (V)	Severe damage to one road tunnel. Causes: Loosened and instable surrounding rock collapsed onto the lining and broke it.
1993 Hokkaido-nansei-oki	7.8	Japan Sea. 86 km west of Suttsu, Hokkaido	34	Okushiri Isi, and western Hokkaido (VI–V)	Causes: Severe damage to one road tunnel due to a direct hit at the portal of falling large-scale rock.

*(In brackets, depth accordingly to database of /Sharma and Judd, 1991/)

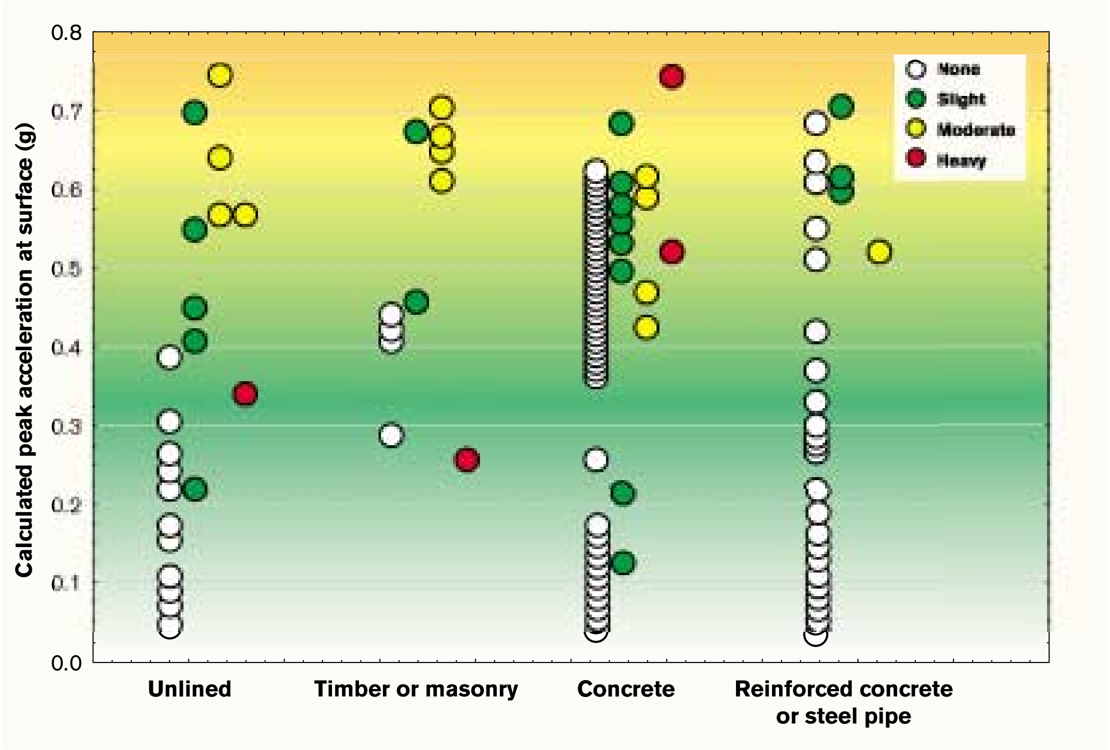


Figure 2-6. *204 case histories of shaking-induced damages from 10 earthquakes were re-analysed by /Power et al, 1998/ including data from 1989 Loma Prieta, 1993 Hokkaido, 1994 Northridge and 1995 Hyogoken-Nanbu (Kobe) earthquake. Moment magnitude is in the range 6.6–8.4. The three cases with Heavy Damage are all from the 1923 Kanto earthquake, Japan, where damage may have been due to landsliding. The damage classification used in the published paper is unfortunately not very precise /Revised after Power et al, 1998/.*

3 Countrywide overviews of data on earthquake influence

This Chapter provides a countrywide general overview of cases on earthquake influence on underground facilities. The cases and presentations made are directed to study the effects of faulting rather than effects of shaking if such information is available. The relevance of the results for a deep repository of spent fuel is later discussed in Chapter 4.

3.1 China

The description of earthquakes in China is limited to the most disastrous earthquake in the 20th century, the Tang-Shan M=7.8 earthquake.

On July 28, 1976 at 3:42 a.m., an earthquake of magnitude 7.8 struck near the east coast of China. The epicentre was near Tang-Shan, an industrial city with a population of about 1 million people, Figure 3-1. Tang-Shan lies on a block of continental crust bounded by major faults. The Tang-Shan earthquake caused a 150 km surface rupture. An estimated 500 000 to 650 000 people were killed.

Ninety-three percent of residential buildings and seventy-eight percent of industrial buildings were completely destroyed. Eighty percent of the water pumping stations was seriously damaged and the water pipes were damaged throughout the city. Fourteen percent of the sewage pipes were severely damaged. The foundations of bridges gave way, causing the bridges to collapse. Railroad lines bent. Roads were covered with debris as well as riddled with fissures. Only one of the roads into Tang-Shan was useable.

Meanwhile, 30 000 miners were trapped underground in several coalmines in the area /McClure and Cole, 1981/ but no loss of lives was reported.

Figure 3-1. *Location of the city of Tang-Shan.*

The experience from Tang-Shan was summarised by /Wang, 1985/. Due to the many witnesses – around 1000 miners were interviewed at the Tang-Shan mine – it was possible to get good statements of the impact of the earthquake from the surface down to around 800 m below surface. The room-and pillar mine also covers an extensive lateral area, providing for a reasonable account of records in the horizontal plane. Around 100 miners were at the Tang-Shan mine production level 640 m below surface where the ore body is around 9 km long and 2 km wide, c.f. Figure 3-3. The classification used by /Wang, 1985/ is a modification of the PRC Seismic Intensity Scale (c.f. Appendix A1.1). This scale is of course developed for effects on surface, but was adapted to the effects at the Tang-Shan coalmine where the intensities were estimated to be Intensity XI at the surface and VII at lowest at depth.

The intensity was highest along and next to either side of the fault lines. Intensity did fall two units within 200 m to 800 m of the faults. The rate of intensity reduction with distance at depth was much more rapid than the rate of reduction with distance observed on the surface. The effects on the miners were dramatically described in the paper. At the adit, people were hurled 2 to 3 m due to the earthquake and at the 230 m level people lost balance, while at 450 m level they were shaken to their knees. Rooms and tunnels at 30 m depth suffered cracks and partial collapse, while only a few cracks in the masonry occurred at depths of 230 m and 450 m. Pieces of rock and mortar fell in a vertical shaft at level 510 m. Pieces of mortar fell at the level 640 m but at level 750 m only shaking occurred. The author also correlated intensity with depth on two other nearby mines, the Zhao-Ge-Zhuang and the Ma-Jia-Gou mine and plotted intensities with depth, see Figure 3-2. It is apparent that the intensity dropped by 3–4 units at a depth of 500 meters below the surface. /Wang, 1985/ concluded that intensity underground decreases rapidly with depth to approach a constant value.

The main conclusions from the Tang-Shan earthquake can be summarised as follows:

Earthquakes that completely destroyed the infrastructure at the surface (Intensity XI) were reduced by several units of intensity underground. At 600 m depth the Intensity was around VII meaning loose objects will fall and that it is difficult to keep a standing position. Intensity could decrease a few units 200–800 m from faults that move. The implied Intensity IX created bending of rails, hurling of people and displacement of mining equipment. However, no serious damage to the overall rock stability was noted.

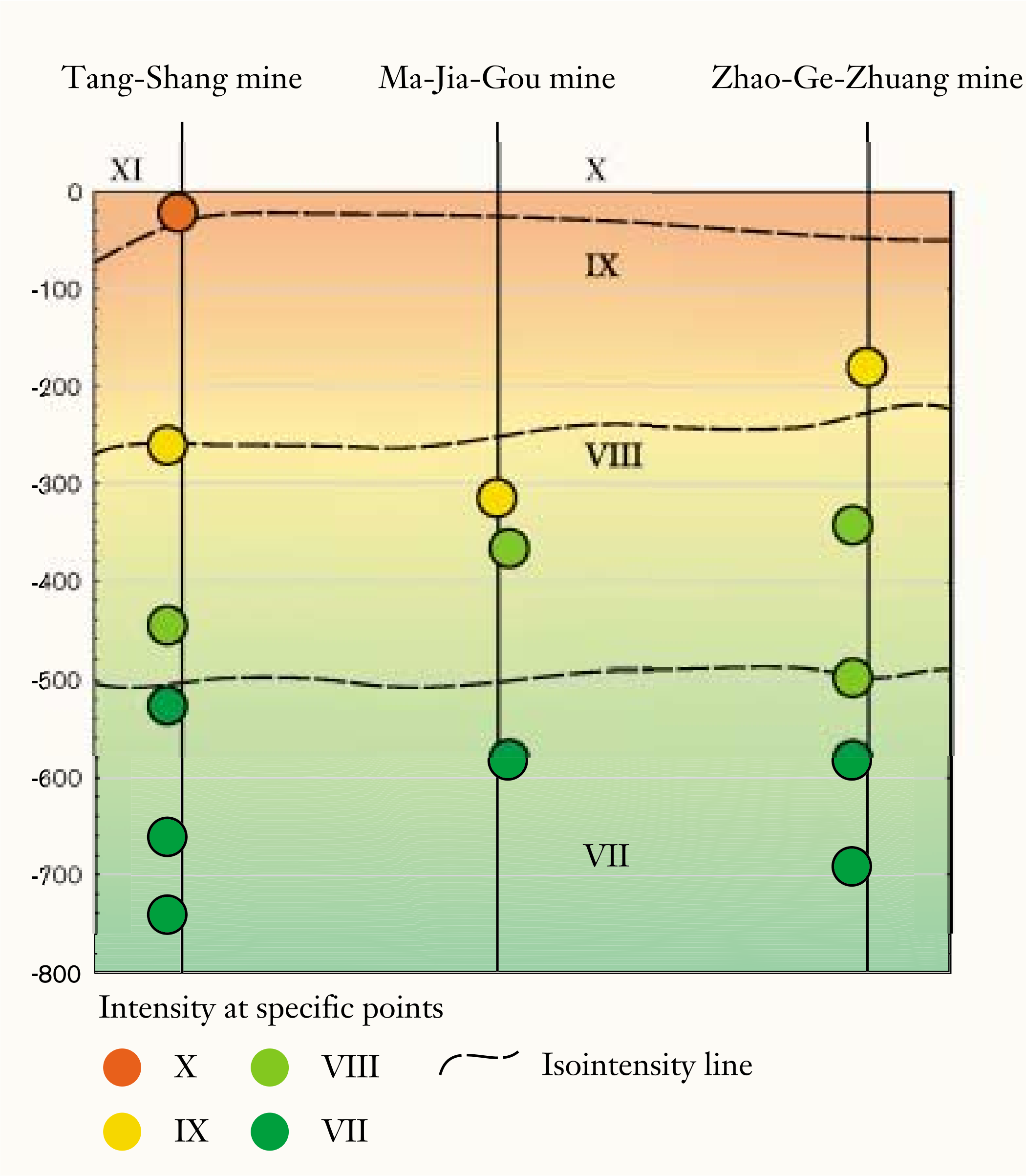


Figure 3-2. Profiles of intensity with depth in metres for three mines in the northern part of the Tang-Shan coal mining district /Revised after Wang, 1985/. The Intensity dropped by 3–4 intensity units at a depth of 500 meters.

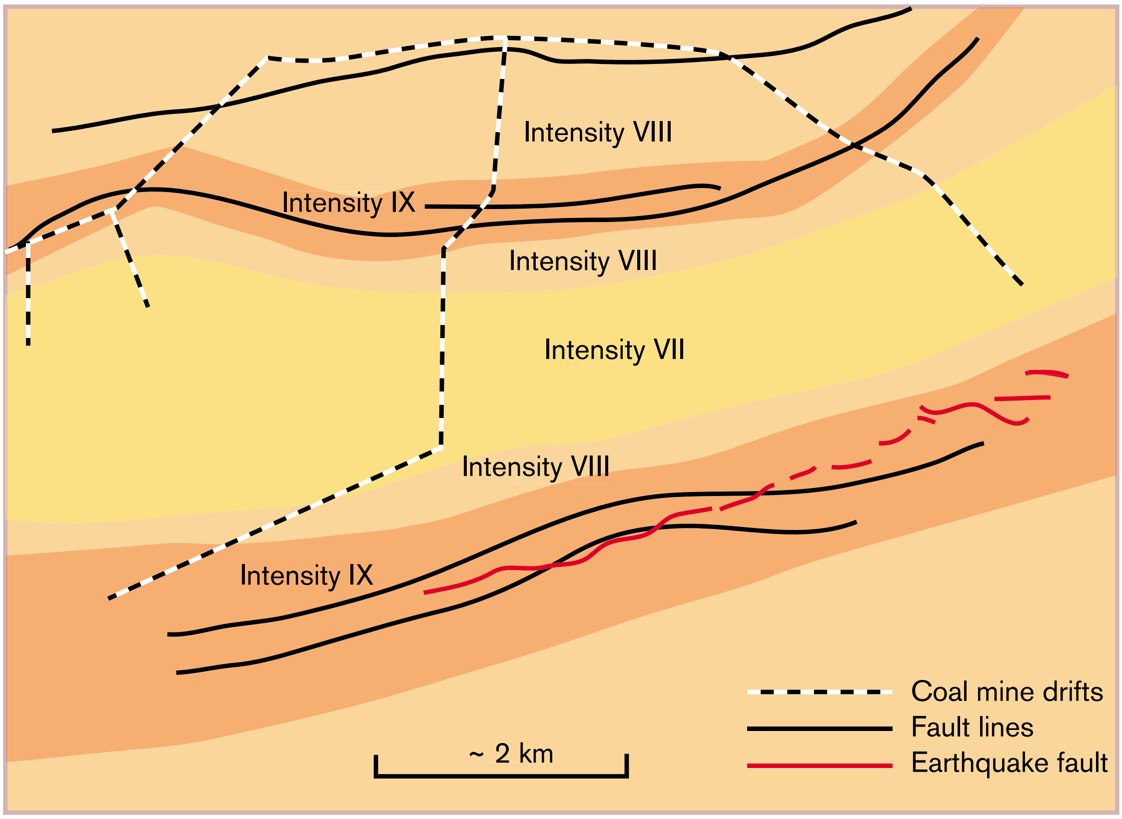


***Figure 3-3.** The figure illustrates the variation of intensity at the 650 m level below surface. The drifts (hatched) cross e.g. fault lines and the intensity variations were estimated by impacts on personnel, equipment and on the rock /Revised after Wang, 1985/.*

3.2 Italy

The earthquake that hit Southern Italy in the Campania district November 23, 1980, was the first unambiguous historical surface faulting in Italy.

The faulting by reactivation /Pantosti et al, 1993/ generated an earthquake that killed 2570 persons, injured some 7500 people and devastated 70 towns and villages. The paper by /Cotecchia et al, 1986/ describes the effects on the Pavoncelli tunnel and surroundings. Figure 3-4 shows the location of the tunnel and the basic earthquake data.

The construction of the 15.6 km long Pavoncelli tunnel through the Appennines tunnel started 1904 and was completed in 1914 as a part of the 244 km long Apulian water supply system. The structural geology of the sedimentary rock is among the most complex in peninsular Italy. Even before the tunnel construction was completed, severe problems were encountered due to the high pressures on the lining of brick masonry due to squeezing rock. The tunnel was later completely re-built in the 1920'ies. The Irpinia magnitude 6.8 quake, focal depth of 16 km and a distance of around 20 km caused damage to the tunnel (to be expected if M=6.8 and R=20 km are inserted into Figure 2-3). The estimated peak ground acceleration was estimated to be in the range of 0.3 g and this acceleration would cause "minor damage". The 1980 earthquake produced permanent deformations of the lining and also at points where no previous damage had been recorded. Figure 3-5 describes the location of damage for the tunnel with overburden 40–400 m and Table 3-1 the damage.

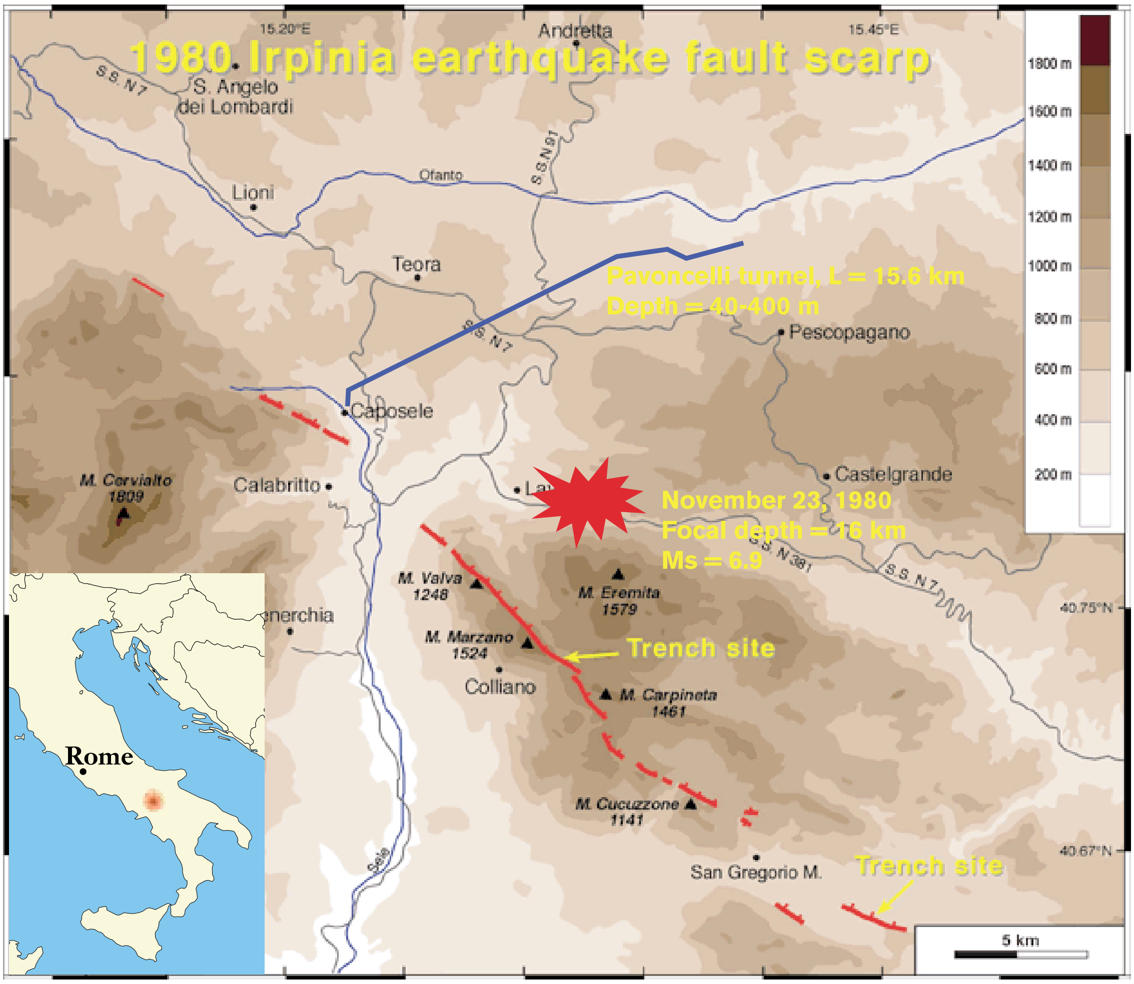


Figure 3-4. *Location of the Irpinia earthquake and the Pavoncelli tunnel /Revised after Pantosti et al, 1993; Pantosti and Valensise, 1990/.*

Figure 3-5. *Longitudinal profile of the Pavoncelli tunnel in Italy and location of the most important damages (c.f. Table 3-1) induced by the November 23, 1980 M=6.8 earthquake. Strong tectonic stresses developed during the earthquake and some faults were reactivated /Revised after Cotecchia et al, 1986/.*

Table 3-1. Description of damage due to the Irpinia November 23, 1980 earthquake /After Cotecchia et al, 1986/.

Section (m)	Damage
1/115–1/125	Cracks along spring line between arch and side walls.
1/225–1/235	Rupture and breakaway of invert from side walls.
2/190–2/200	Uplift of invert.
4/100–4/120	Maximum uplift of invert 0.5 m.
4/450–4/472	Maximum uplift of invert 0.9 m and cracks in arch and side walls.
4/600–4/800	Maximum uplift of invert 1.6 m (at 4/698), crushing of lining blocks, breakaway and collapse of part of roof and side-wall masonry, especially at the spring line.
4/880–4/950	Maximum uplift of invert 0.5 m.
5/050–5/065	Rupture and uplift of invert 0.5 m.
8/910	Whole section of tunnel sliced with shift in the longitudinal and transverse direction, see Figure 3-6.
9/300–9/350	Widespread cracks in all the arch and side-wall masonry, with maximum opening of 4–5 cm in a transverse crack on the side wall, maximum uplift of invert 0.45 m.

The paper by /Cotecchia et al, 1986/ reports that some faults were reactivated during the earthquake. There was also a correspondence between damage location and lithological changes. An example is shown in Figure 3-6. The tunnel displaced at the contact between two different soft rock types with different plasticity properties.

Figure 3-6. *Pavoncelli tunnel. Rupture of lining at transition from Varicoloured clays to Pliocene blue clays of the Ofanto Basin. Photo from chainage 8910 /Cotecchia, 1986/.*

3.3 Japan

The Japanese islands are squeezed between the Pacific, Philippine, Eurasian and the North American plates. The plate motions and active volcanism cause frequent earthquakes. In Japan and the surrounding region, around 43 $M \geq 4.0$ seismic events are recorded per month as an average for the past thirty years. Four of them are $M \geq 5.0$. In average, one $M \geq 6.0$ earthquake occurs every month.

There are (year 2001) 2281 classified active faults in the Japanese islands. An active fault is defined as a fault that has reactivated during the Quaternary Period to form distinct displaced landform at the surface, /RGAF, 1991/. The faults are also classified accordingly to slip rate (in meters) per 1000 year. There are 103 Class A faults with slip rate > 1 m/1000 years, 884 Class B faults with slip rates 0.1–1 m/1000 years and 660 Class C faults with slip rates < 0.1 m/1000 years. The number of Class D faults with slip rates < 0.01 m an/1000 years and faults with unknown slip rates is 634.

Due to the mountainous topography of Japan, tunnels are used extensively both in the railway and highway systems. There are 4764 railway tunnels in Japan (data from 1995) with a total length of about 3000 kilometres. There are an additional 6500 highway tunnels with a total length of 1800 kilometres. In addition, tunnels are used extensively in hydroelectric projects, for water supply, and for access to underground storage facilities.

Viewed in this context, there are surprisingly few reports on severe damage to tunnels in Japan. This is partly because there is good present-day know-how to select proper design and construction of the tunnels. This section summarises part of the available information in English where important damage is recorded. As stated in the paper by /Yoshikawa and Fukuchi, 1984/ there were at that time (1984) only four earthquakes that caused so much damage that the tunnels needed restoration or re-construction. Here we will later focus on the damage to the Tanna tunnel and the Inatori tunnel /Kawakami, 1984/ as these damages were caused by a fault crossing the tunnels. The disastrous Hyogoken-Nanbu (Kobe) earthquake 1995 also caused damage to tunnels and there are several papers /e.g. Asakura and Sato, 1998; Otsuka et al, 1997/ that describe the damage. The western Tottori earthquake in October 2000 is also of interest as the earthquake fault displaced a tunnel. Figure 3-7 shows the location of sites discussed in following sections or later in the report.

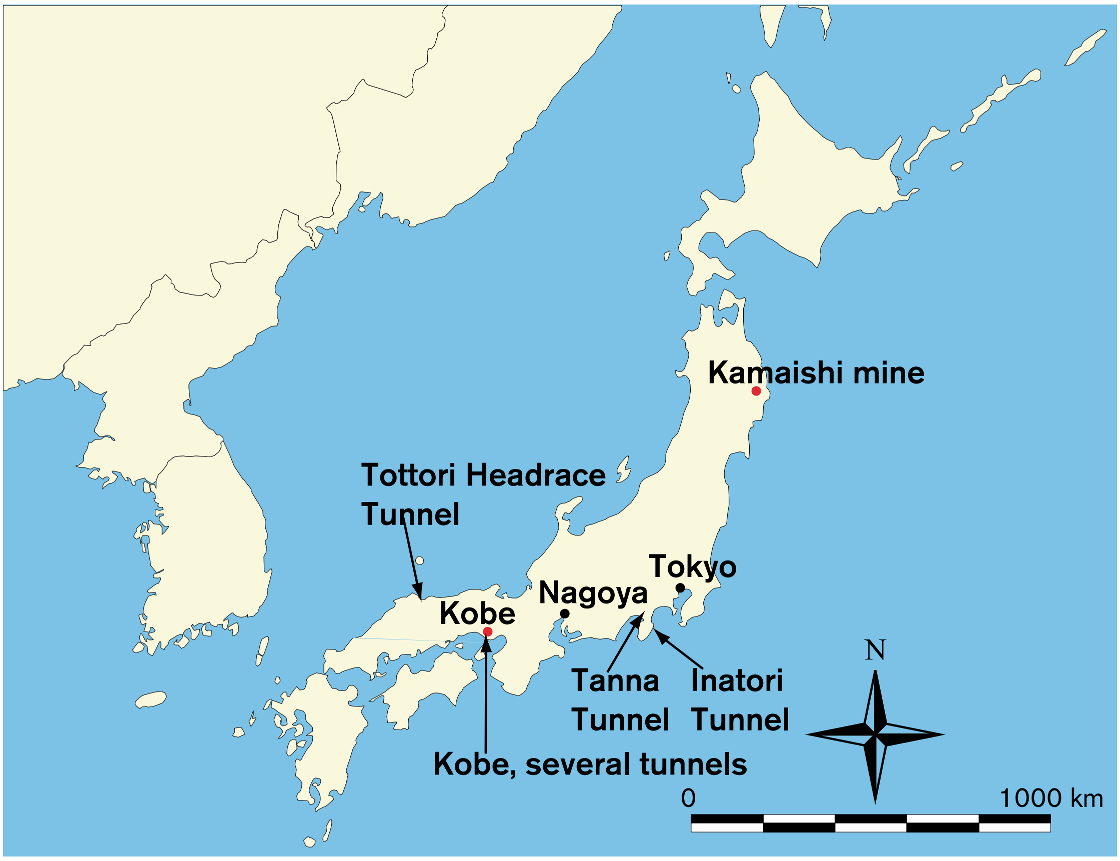


Figure 3-7. *Map of Japan and location of sites that are discussed in the report.*

3.3.1 Kita-Izu earthquake

The report by /Brown et al, 1981/ stated that the Tanna railway tunnel between Atami and Mishima, located South-East of Mount Fuji, was under construction when it was damaged 26 November 1930 by the Kita-Izu magnitude 7.1 earthquake (focal depth 11 km and epicentre distance of 15 km /Sharma and Judd, 1991/). /Bonilla, 1979/ summarised several Japanese reports and reported that the North-South surface rupture was 24 km long, not including some minor ruptures. The middle part of the surface faulting consisted of a double trace 1 km apart. The rupture in the tunnel with 160 m of overburden took place in a breccia zone. The section at the tunnel consists of 45 m of sandy clay lake deposits overlying lower Pleistocene tuff, agglomerate and lava flows. /Takahashi, 1931/ wrote that almost all strata cut by the tunnel was of soft materials, such as sand, volcanic scoria, agglomerate and clay. Due to the poor rock he mounted his measurement devices in the concrete lining instead of in the rock. Very wet tunnelling conditions required drainage drifts around and ahead of the main tunnel during the period of construction. Near the heading of one of the drainage tunnels, an existing shear zone displaced laterally 2.7 m and horizontally 0.6 m due to the earthquake. The drainage drift was completely closed; however only a few cracks appeared in the main tunnel walls, in spite the main tunnel heading was only 0.5 m east of the active shear zone. The precise levelling of /Takahashi, 1931/ showed that deformation is closely associated to the geology. Deformations were mostly tied to faults or where the strata show sudden change in strength.

3.3.2 Izu-Oshima-Kinkai earthquake

The Izu-Oshima-Kinkai earthquake struck 14th January 1978 and severely damaged nine railway and four road tunnels in a limited area. Twenty-five persons were killed. The earthquake had magnitude 7, the focal depth of 3 km and an epicentral distance to the Inatori railway tunnel of 23 km (Figure 3-8). Fault data are shown in Table 3-2.

The length of the subsidiary fault was estimated from the surface expression. On the ground, the fault was manifested by a group of regularly arranged ground fractures. Individual fractures were generally a few meters long and essentially tension fractures. The en-échelon arrangements of these fractures constitute a fracture zone 100–700 m long, which make up the subsidiary surface fault segment of around 3 km /Tsuneishi et al, 1978/.

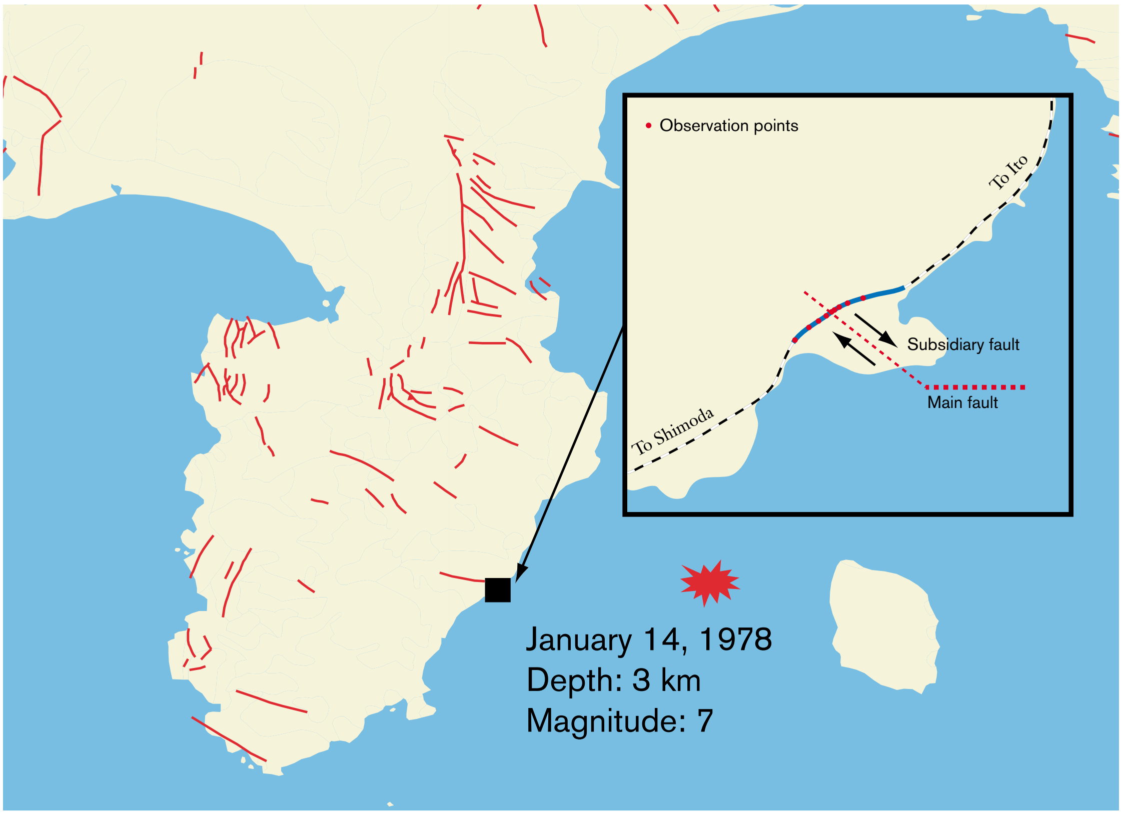


Figure 3-8. *Location of the Inatori tunnel (Data from /Kawakami, 1984; Murano and Takewaki, 1984/ and JMA earthquake catalogue). The observation points are used in diagrams Figure 3-9.*

Table 3-2. Data for the main and subsidiary fault /After Kawakami, 1984/ (c.f. Figure 3-9).

Parameter	Main fault	Subsidiary fault
Fault length (km)	17	3
Fault width (km)	10	1.5
Dislocation right lateral strike slip (cm)	183	70
Dislocation normal dip slip (cm)	26	0

The Inatori tunnel is a 6 m diameter 906 m long single-track railway tunnel. Overburden is about 100 m at the most. The tunnel was excavated through a deposit of volcanic mudflow deposits that have been hydrothermally altered to clay. The tunnel was supported with a lining of 0.7 m of concrete /Kawakami, 1984/. The alignment of the tunnel displaced and the transversal and longitudinal deformation is depicted in Figure 3-9. The centre of the tunnel was displaced by 50–70 cm within a zone of 20 m at 440 m from the tunnel entrance (measured from the Ito-side) where a fault segment crossed the tunnel. Transversal kinks of a few decimetres were also recorded at 300–400 m from the main fault for the longitudinal and vertical displacements. These displacements were measured on the concrete lining. The data are relevant if there is a good coupling between the rock and the rail and the rock and the lining. In case the coupling is poor, the data represents what occurs to the lining or rail rather than to the rock. The deformations measured on the lining may also be a result of shockwaves generated by the earthquake, c.f. Chapter 3.3.3 and Chapter 3.6.

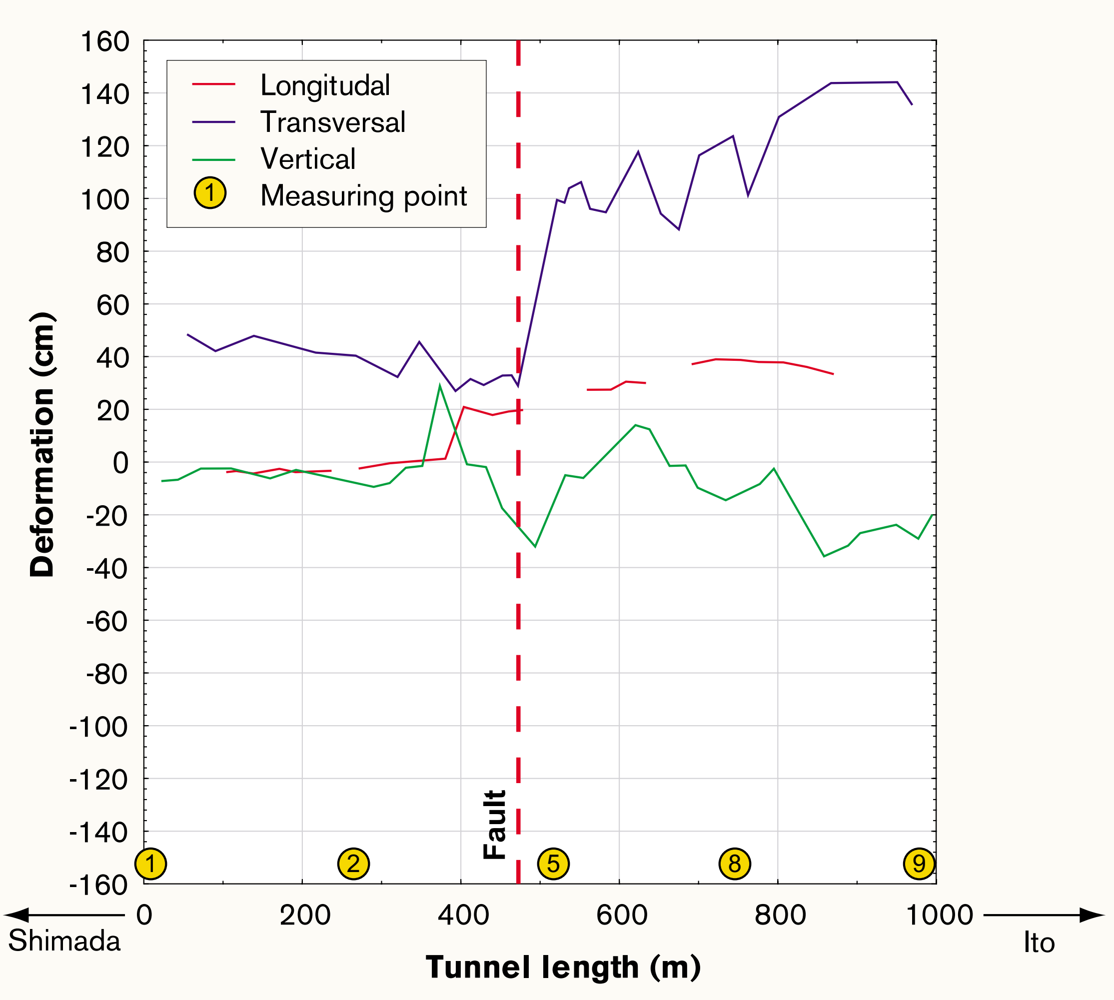


Figure 3-9. *Transversal, longitudinal and vertical displacements along the Inatori tunnel as a consequence of the earthquake /Revised after Kawakami, 1984/. See /Kawakami, 1984; Tsuneishi et al, 1978/ for details concerning the measurements.*

3.3.3 Hyogoken-Nanbu (Kobe) earthquake

A major earthquake occurred near the City of Kobe, Japan Jan 17, 1995. The 7.2 magnitude earthquake had 40 km of bilateral rupture from a hypocenter 17.9 km under the northern tip of the island of Awaji in the Sea of Japan. While the 20–30 km portion of the NE of the epicenter remained concealed the SW rupture portion formed 10 km of significant right-lateral oblique strike slip surface faulting along the Nojima fault on the NW side of the Awaji Island. Slip varied along the strike reaching a maximum 1.7–1.9 m of horizontal displacement and a maximum of 1.25 m vertical displacement. The earthquake caused 5480 fatalities, the highest death toll in Japan since the Great Kanto Earthquake of 1923 (142 000 deaths). About 94 900 people were injured. More than 192 700 houses and buildings were totally destroyed by the earthquake. The design code in effect at the time of the construction was a major factor in determining the extent of damage to the commercial and residential buildings. Modern high-rise buildings typically fared better than older residential construction. There is an abundance of papers describing this earthquake. Here, we concentrate on works of /Asakura and Sato, 1998; Murakami and Hoshino, 1997; Otsuka et al, 1997; Yamaguchi and Tsuchiya, 1997/. Figure 3-10 shows an overview of the locations of tunnels described in this report.

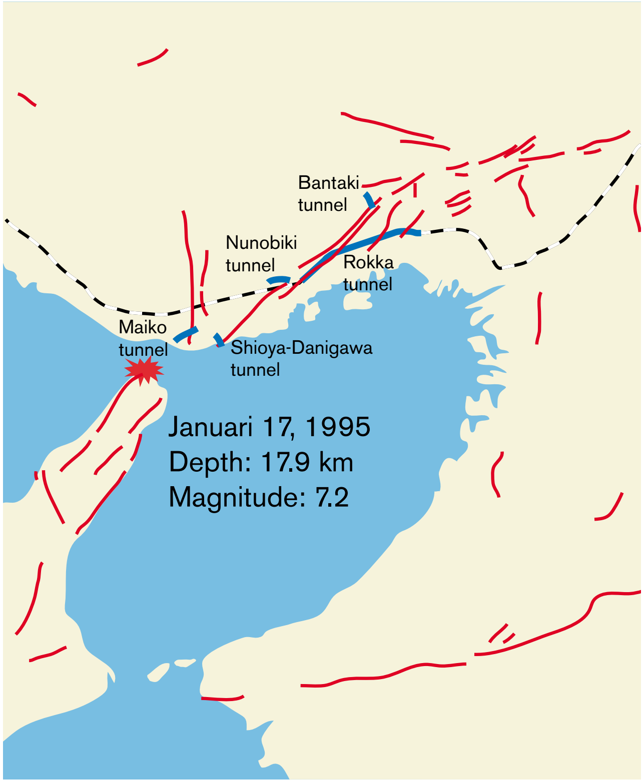


***Figure 3-10.** Overview of the Hyogoken-Nanbu (Kobe) earthquakes, fault lines and locations of a few of the 30 road tunnels and 69 railway tunnels in the area /Asakura and Sato, 1998; Otsuka et al, 1997/.*

There are 107 rock tunnels in the area, not counting cut-and-cover tunnels and tunnels constructed by shield tunnelling. Damage was observed in 24 tunnels. Twelve tunnels were reported as requiring repair and 12 with minor damage not requiring substantial repair. Typical damage patterns were cracking in the lining, spalling of concrete in the arch and the sidewalls, expansion of existing cracks, heave and cracking of the invert, settlement of the arch crown, pounding of construction joints, collapse of portal /Asakura and Sato, 1998/.

The closest tunnel, the Maiko tunnel under construction, with an epicentral distance of 4 km received only slight damage while a four-story building on the surface on top of the tunnel was completely destroyed. There was, however, no definite regularity of damage relative to the epicentral distance for the 12 most damaged tunnels. They were all within ~10 km from the presumed earthquake plane. A great part of the damage was caused where faults are crossing the tunnels, c.f. Figure 3-10. Only the Nojima fault was confirmed to be displaced by the earthquake. Whether or not other faults have been displaced is not certain /see Otsuka et al, 1997/. Table 3-3 provides some basic data for the tunnels. Estimating the peak ground acceleration based on Figure 2-3 would produce PGA in the order of 0.25–0.3 g (hypocentral distance 18–35 km) and damage due to shaking would be expected. /Power et al, 1998/ estimated PGA to around 0.6 g.

Table 3-3. Overview of a few damaged rock and railway tunnels in the Kobe area /After Asakura and Sato, 1998; Otsuka et al, 1997/.

Tunnel Rock support	Overburden (m)	Rock Type	Epicentral distance (km)	Damage
Maiko Concrete lining (3-lane – per tube – road tunnel under construction)	4–50	Granite Sand-gravel	5	Exfoliation and cracking of shotcrete, crown settlement.
Nunobiki (2-lane road tunnel)	240	Mesozoic granite	18	Exfoliation of concrete lining, ring-shaped cracking at lining concrete; loosening and exfoliation of joints
Bantaki (2-lane road tunnel)	20–250	Mesozoic granite	32	Exfoliation of concrete lining in certain sections where a fault crosses the tunnel. At other points ring cracks developed in the lining.
Rokko (16 km long Shinkansen tunnel)	0–400	Mesozoic granite	20–30	Damages at 12 locations, like shear cracks and spalling of lining, heave of the floor. Almost all damages coincide with fracture zones that were recorded during the construction.
Shioya-Danigawa (River tunnel)	4–80	Granite	8	At the Yokooyama fault crossing the tunnel displaced right-laterally 1 cm and upward 5 cm relatively to the southeast (downstream) side. This movement resulted in 8-cm lateral and 5 cm vertical relative displacement of the lining and many cracks in the arch, side walls and invert concretes within a 10 m long zone around the fault crossing.

The Rokko tunnel in granitic rock, one of the very famous tunnels in granitic rock in Japan, is of special interest. The 16 km long Shinkansen tunnel east of Kobe was constructed in the early 70'ies. The Kobe 1995 earthquake severely damaged the tunnel, Figure 3-11, and it was closed down for almost four months. One interesting aspect is that the tunnel section was affected by shockwaves. The opening size was undulating ± 30 cm compared to the original shape. Modelling by Dr T Asakura (pers. comm.) does not replicate this mode of deformation. Damage, probably due to shaking, was mostly confined to the location of faults. The granitic rock is, however, very poor and weathering is common where the overburden is small. There are a few active faults intersecting the tunnel, but also frequent minor faults. The best parts of the rock have uniaxial compressive strength of around 100 MPa, and only a few MPa in the poor rock. During construction there were immense water problems. The inflowing water was drained. At one occasion, 16 drainage tunnels (area 10 m^2) were constructed around the main tunnel to make tunnelling feasible. Water inflow was in the range of 0.5–1 m^3/s. Flowing ground conditions at the tunnel face were a common feature.

In summary, the disastrous earthquake at Kobe that caused an enormous devastation at the surface indeed also damaged tunnels in rock. This damage can be classified as cracking and exfoliation of lining concrete at portals and at other places where the depth is shallow, and cracking, exfoliation and falling of lining concrete at the sections where a fault crosses the tunnel. Records, where available, on damage of tunnel lining due to fault movements show that damage took place within ~10 m from the faults.

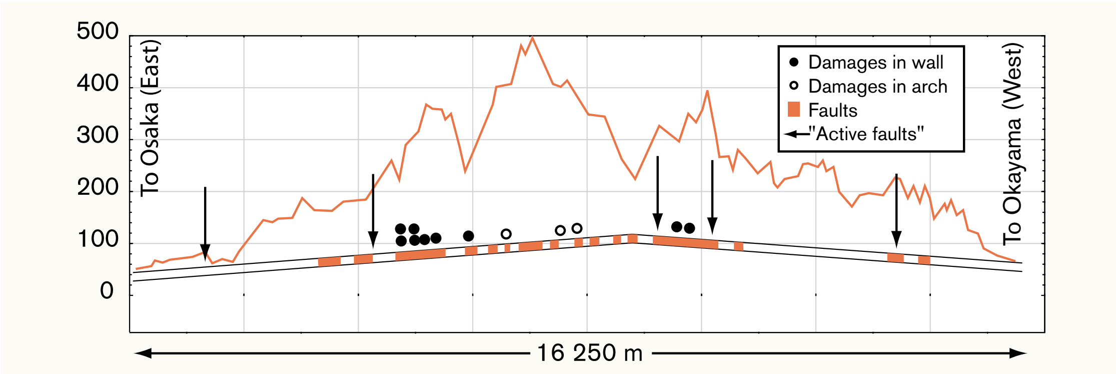


Figure 3-11. *Damage in the Rokko tunnel caused by the Hyogoken-Nanbu (Kobe) earthquake. The granitic rock is of very poor quality and most damage is at or close to the fracture zones /Revised after Asakura and Sato, 1998/.*

3.3.4 Western Tottori earthquake

The Western Tottori earthquake occurred on October 6, 2000. The strong M_{JMA}=7.3 earthquake had the focal depth of 10 km. One interesting aspect is that the surface rupture occurred at a place where no active faults had been identified in the map scale of 1:2 000 000. However, later investigations in the scale 1:10 000 confirmed the existence of an active fault. The distribution of aftershocks mostly coincides with traces of this fault. CRIEPI, the organisation conducting investigations, suggests that the active fault is a part of the earthquake source fault.

One headrace tunnel located 200 m below the surface for a hydropower plant intersects the rupturing fault, Figure 3-12, The tunnel is below a lineament that can be found in detailed aerial photographic interpretation. Damage was mostly confined to the area where the tunnel intersected the fault with left-lateral deformation of 10–20 cm, Figure 3-13.

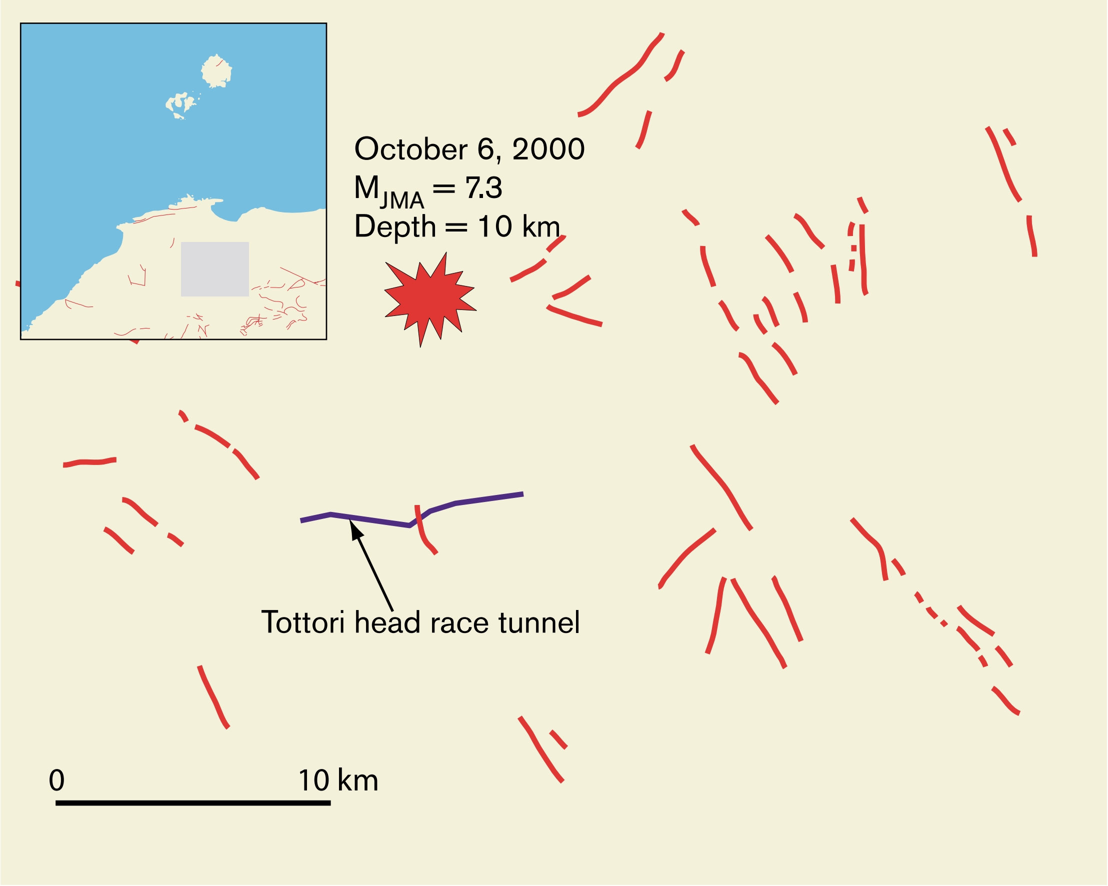


Figure 3-12. *Location of damaged headrace tunnel and faults. Faults are in red colour and the tunnel in blue colour /Revised after Ueta et al, 2001/.*

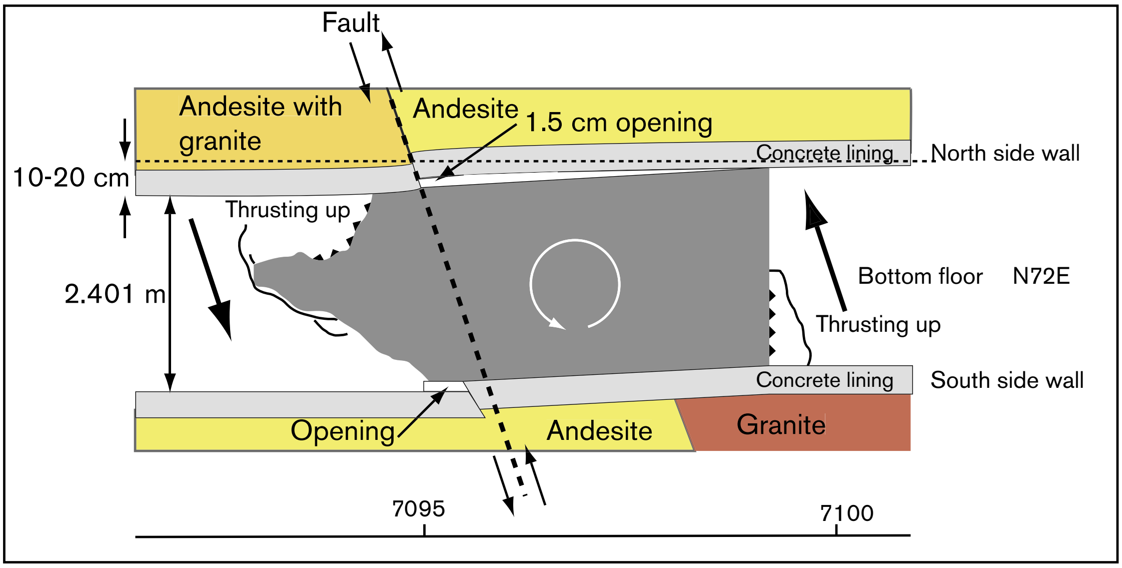


Figure 3-13. Schematic diagram showing deformation of the headrace tunnel associated with the left-lateral faulting at one location /Revised after Ueta et al, 2001/.

3.3.5 Miscellaneous information

Concerning earthquakes, the around 4800 railway tunnels with a total length of 3000 km have in general remained stable. The first serious tunnel closure in Japan was a cut-and cover underground station that was damaged at the Kobe 1995 earthquake. The Hyogoken-Nanbu (Kobe) earthquake required change of previous design codes. The new design code, /RTRI, 2001/also includes historic information of earthquake damage to tunnels, Figure 3-14. Damage classification is functional. *Heavy Damage* means stop of operation for a long time, *Moderate Damage* is stop of operation for 2–3 days and *Slight Damage* is damage that does not affect the immediate function of the tunnel. The numbers in Figure 3-14 denotes the number of damages. Railway tunnels has thus performed sufficiently well for magnitudes > 7 and at larger distances than 30 km from the surface fault line without any *Moderate Damage*.

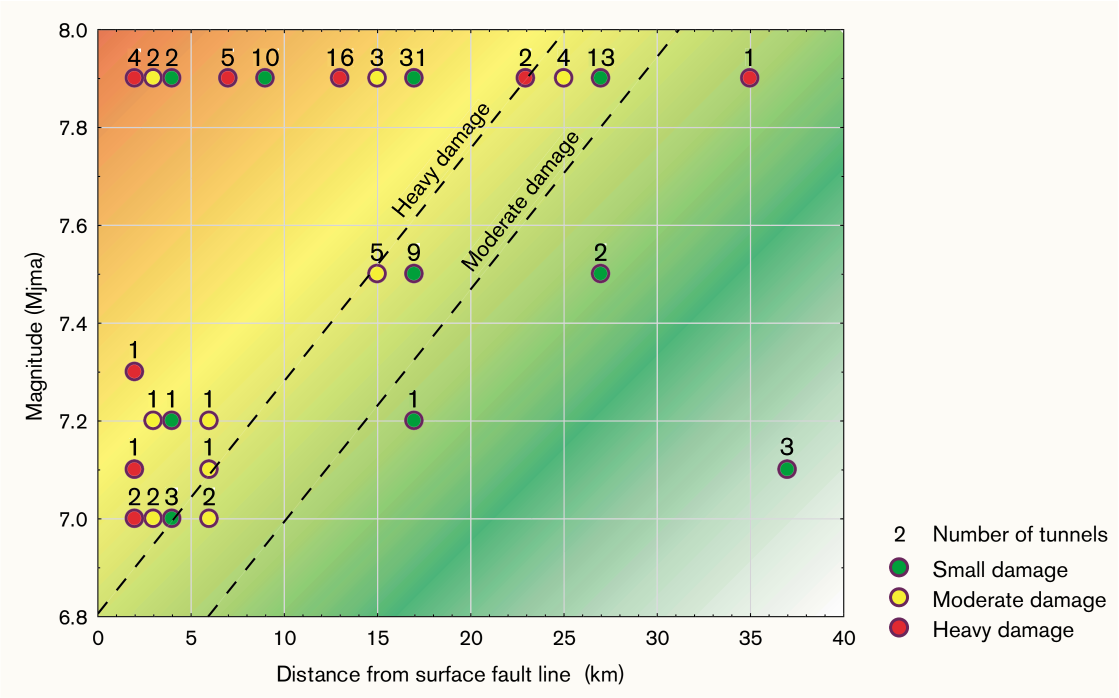


Figure 3-14. Damage to railway tunnels as a function of distance and magnitude. The figure includes all damages, also damages caused by e.g. poor concrete etc. (construction flaws). There are very few railway tunnels in granitic rock, the Rokko tunnel being an exception also because of the depth to the surface. Normally the tunnels are at low depth and in sedimentary rocks. 40% of the JR railway tunnels were constructed before 1940 /Revised from RTRI, 2001/.

3.4 Russia

The paper of /Bezrodny, 1999/ described the effects of earthquakes on a few tunnels in Russia. The Krugobaikalskaya railway, completed in 1904, is situated along the shore of the Baikal Lake and is a part of the Trans-Siberian Railway. The 85 km section from Baikal to Kultuk has 38 tunnels. The rock type is fractured gneiss-granites. There is no certain connection between the rock and the lining. Since the construction of the tunnels, four M=7 and five M=5–6 earthquakes have occurred, the closest (Sept 28, 1904) being 70 km away. Damage due to earthquakes has occurred due to landslides and shift of rock masses along faults. No damage has been reported at all for tunnels with overburden depth over 10 m.

/Bezrodny, 1999/ also described the construction of the Severomuisk railway tunnel. Even quite small earthquakes had impacts. It is reported that magnitude 3 earthquakes caused deformations of 0.01–0.1 mm and that some earthquakes caused outflow of water from faults (70–1000 m^3/h). According to /Bezrodny, 1999/ all problems of construction were confined to faults where the soils reached the critical strain level of 10^{-3}. There are no reports of failures where the fault zones were secured by pre-grouting.

3.5 South Africa

There are presently around 30 seismic networks in operation in South African mines with around 1500 channels. These pick up an estimated 2.5 million seismic events per year, providing full waveforms. The mining-induced earthquakes attract seismologists worldwide, as they have good opportunities to study the earthquake nucleation process in the mines. Most events are associated to fault slip. As the mining proceeds, mining drifts occasionally intersect the faults and it is thus possible to study the actual slip surfaces and adjacent rock in detail.

Gold mines are operated at great depths in South Africa. The deepest mine (2001) has proceeded to 3800 m below surface. While only 5% of the production is below 3 km depth, it is anticipated that 40% of the gold mining will take place below 3 km already in year 2015 /Durrheim, 2001/. The quartzitic hostrock harbours the ore formation constituted by the Vaal Reef Conglomerate and dykes. Figure 3-15 illustrates schematically the mining and associated mining-induced seismic events.

The gold occur in cm-narrow veins. The orebody extends for several km in length and some km in width. Typical strength data based on uniaxial compressive tests are 320 MPa for the dykes, 220 MPa for the ore formation and 180–240 MPa for the host rock. Due to the extensive regional mining for decades, it is not possible to derive the primary stresses, but data from the 1980'ies and experience implies that the vertical stresses represent the weight of the rock and the horizontal stresses being 65% of the vertical. This means that vertical stresses are around 55 MPa vertically and 35 MPa horizontally at the depth of 2 km. The stresses are isotropic in the horizontal plane. The traditional mining method is longwall mining; as the mining extends outwards, the central stope is closed due to the convergence caused by the extraordinary high stresses at depth. Around the openings, the rock is completely fractured, within what is called the "process zone", but secured by rock support systems. Seismic events are in most cases mining-induced fault slip. However, in the absence of fault systems that can accommodate deformation, "shear ruptures" occur in intact rock.

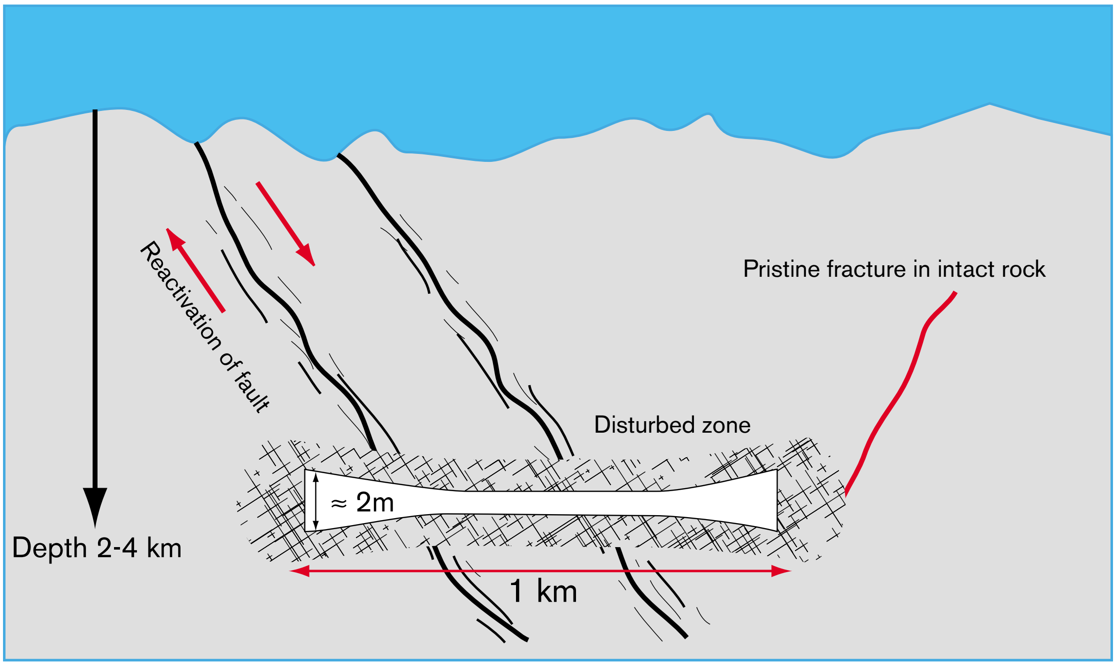


Figure 3-15. *Sketch showing typical mine situation in South Africa and associated mining-induced earthquake effects.*

Around one fatality occurs per 1000 employees, and year in the South-African mines. 18% of the fatalities are due to rockburst. Year 2000, around 50 miners out of a workforce of 220 000 in South Africa were killed due to rockburst. Application of proper backfilling technology in the ultra-deep Tau Tona mine has drastically reduced the number of rockburst, fatalities and serious injuries in the mine /Murphy, 2001/.

Table 3-4 describes typical seismic events and their source mechanisms. The South African definition for rockburst is "*a seismic event which violent and significant damage to a tunnel or excavations of a* mine" /Ortlepp, 2001a/.

There are many reports on the damages caused by these mining-induced earthquakes /Durrheim et al, 1997; Lenhardt, 1988; Wagner, 1984/. /Wagner, 1984/ calculated the peak velocities based on /McGarr et al, 1981/-relation as:

$$\log(\mathbf{v}) = 3.95 + 0.57 \cdot \mathbf{M} - \log(\mathbf{R}) \qquad 3\text{-}1$$

where **R** is in cm and **v** in cm/s and **M** is the magnitude.

Wagner concluded that peak velocities in excess of 2 m/s were particularly hazardous to the mining operation.

The paper by /Lenhardt, 1988/ reported 391 events in the magnitude range 0–3.1. Of these events, 57 were reported as damaging meaning the earthquake resulted in at least one panel shift of operation lost. Lenhardt confirmed the experience by /Langefors and Kihlström, 1963/ that stone falls occur at the peak velocity of 30 cm/s and that fractures in the intact rock occur at around 60 cm/s. The data is depicted in Figure 3-16.

Very extensive mining over many years can change the regional stress field and cause major seismic events. An earthquake, M_L=4.6 hit the town of Welkom, 250 km SW of Johannesburg in January 1989. A 2 km long fault, intersected by several mine workings, was re-activated. The co-seismic slip was estimated at 400 mm but damage to rock walls was almost insignificant /Ortlepp, 2001a/.

Table 3-4. Classification of seismic event types /After Ortlepp, 2001a/.

Seismic event	Postulated source mechanism	First motion from seismic records	Richter magnitude M_L
Strain-burst	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	−0.2–0
Buckling	Outward expulsion of large slabs of pre-existing parallel to surface of opening	Implosive	0–1.5
Face crush/ pillar burst	Violent expulsion of rock from stope face or pillar sides	Mostly implosive, complex	1.0–2.5
Shear rupture	Violent propagation of shear fracture through intact rock mass	Double-couple shear	2.0–3.5
Fault-slip	Sudden, renewed movement on existing fault or dyke contact	Double-couple shear	2.5–5.0

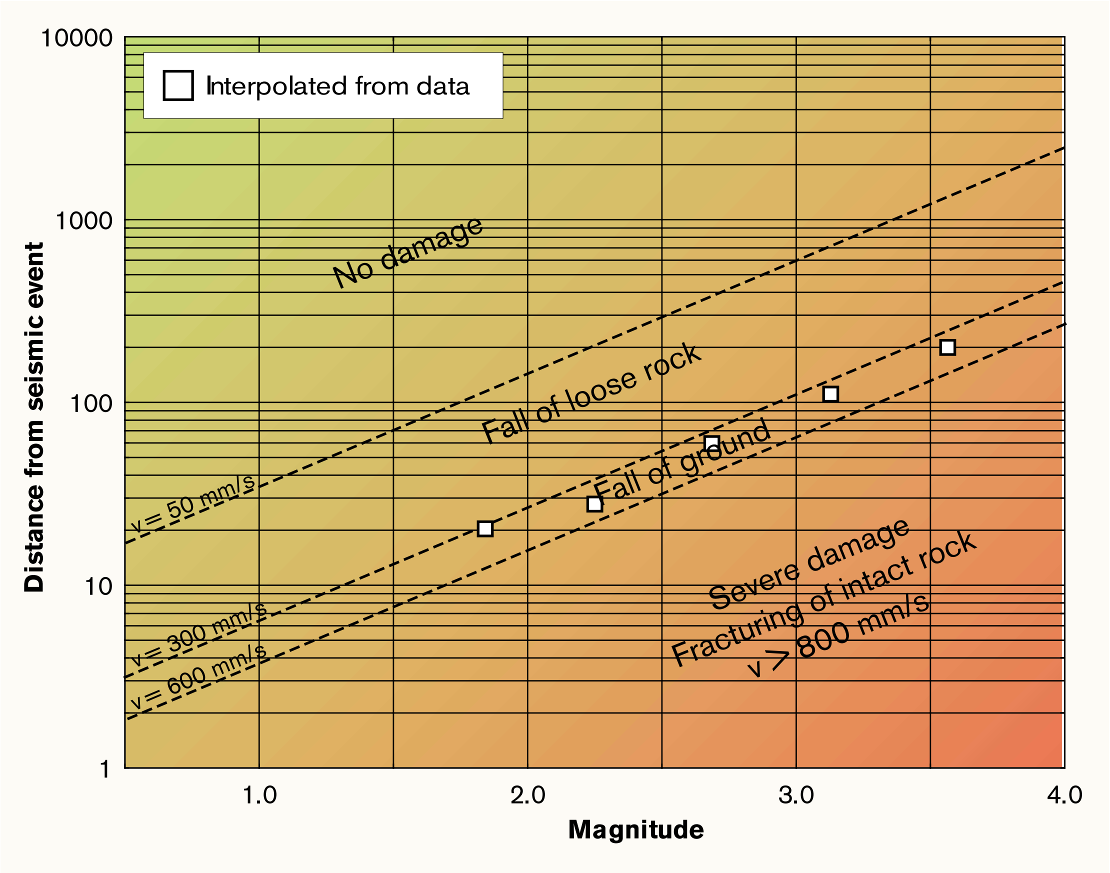


Figure 3-16. *The data from damages in the Western Deep Level gold mine (South Africa) supports that the peak velocities of 30 cm/s and 60 cm/s respectively are useful to decide the probability of fall of loose rocks and damage to intact rock /Revised after Lenhardt, 1988/.*

The paper by /Ortlepp, 2001b/ provided a comprehensive overview of 25 years of research into a suite of aspects like source mechanisms and mechanisms of damage. Seismic events were for most cases mining-induced fault slip. However, it was recently re-suggested /Ortlepp, 2001b/ that in very high stress regimes, ”shear ruptures” may be formed. These ruptures form where there are no faults that can accommodate the energy build-up caused by mining. Due to the “process zone” where rock at the stope face is fragmented due to the very high stresses, it was proposed that “shear ruptures” do not initiate at the stope, but at some point distant from the stope and surprisingly enough not from the stope and outwards, but inwards towards the stope, Figure 3-17. Using a linear elastic model, the deviatoric stresses are supposed to be largest at the opening. In this case the rupture would be initiated at the opening and move outwards from the opening.

Dr Ortlepp has recently acquired data from such a “shear rupture” by tunnelling 30 m along the rupture. In September 1998, a significant suite of three burst ruptures, interpreted as fresh developments of “shear ruptures”, was identified in the # 6 panel of the 50E line of 87 level Western Deep Levels South mine, now known as Mponeng. Ortlepp also provided the important note that the surrounding rock was completely free from faults and that even fractures were extremely rare in this particular instance. The specific rupture studied was created during pillar extraction; the maximum stresses in the rock might have been as high as 400 MPa (Ortlepp pers. comm.).

Figure 3-17. *Photo on a typical "shear rupture" as suggested by /Ortlepp, 1997/. The photo is from Rupture # 18, West Claims. /Segall and Pollard, 1980/ later used the findings from the 70'ies in their famous work.*

In the following, two recent, strong earthquakes are discussed. In April 1999, the Dagbreek fault re-activated due to mining. The Dagbreek fault is around 50 km in length, a few hundred meters wide and dipping 35–40°. The event was recorded as M=5.1. The hypocenter was in the area of the Eland Shaft in the Mathjabeng mine where the Dagbreek intersect the Eland shaft and detailed studies are in progress at the exposures at depth of 1660 m below the surface. The minimum displacement was estimated to around 40 cm. Co-seismic displacements and massive increase of surface area was distributed over many gouge zones over a 30–45 m wide zone. It was clearly demonstrated that new fractures were created in the zone close to the fault. /Dor et al, 2001/. At one site, the apparent slip was 21 cm distributed within 3–5 cm thick, fine grained and fresh gouge zone. At a third site the subsurface rupture included around twenty gouge zones where most of the slip surfaces was coated with white "rock flour" indicating rock bursts. Empty boreholes were used as reference markers at several instances.

The 5th International Conference on Rockbursts and seismicity in Mines (RaSim5) organized September 17, 2001 an underground tour to Shaft # 5 in the African Rainbow Mineral mine. The tour showed underground damage caused by an earthquake M_W=4.2 at the focal depth of ~2300 m below surface. Ms Shana Ebrahim-Trollope, resident mine seismologist and Professor Ze'ev Reches, Hebrew University, Jerusalem were the guides for the visits at the 62, 64 and 68 level, corresponding to roughly the depths of 2050 m, 2150 m and 2350 m below surface. The earthquake took place August 1, 2001 only seven weeks before the tour. A 5 km long ~3–15m wide fracture zone, dipping 60–65° degrees reactivated and caused the earthquake. The USGS in Denver recorded the event as Richter magnitude 5.2 with focal depth < 10 km. The local seismic network in the mine registers down to magnitude –1 with the frequency range of 5 to 500 Hz and the records revealed that a magnitude 3.7 event occurred 0.2 seconds before a M= 4.2 event. At the 62 level (depth 2050 m), drifts penetrated the fault at three different locations. This zone has, in total, slipped 320 m over the geological eons since it was formed. The fault displaced by around 0.20 m as a dip-strike movement at the earthquakes with a seismic stress drop of 6.5 MPa. The research group had derived the kinematic deformations by measuring deformation of the haulage rails. Vertical deformation, including possible elastic and plastic components was less than 0.10 m at a distance at around 20 m from the displaced fault /Reches, 2001/. At the levels visited, the rock damage was localised to some 10 meters from the fault. Rock falls was however scattered over a larger area, Figure 3-18. At the deeper level 70, drifts were completely closed. The event killed two miners.

Figure 3-18. *Examples on shaking damage in the A.R.M Shaft # 5. Drift at the Level 64 (2150 m below surface). The drift is partially collapsed. Photo: G Bäckblom.*

3.6 Taiwan

An earthquake (M_L=7.3) struck central Taiwan in September 21, 1999. The depth of the hypocenter was around 7.5 km and the epicentre close to the Chi-Chi town 12 km to the west of the Sun Moon Lake (Figure 3-19). This earthquake caused serious damage to energy facilities, agriculture, engineering constructions, and lifelines, with 2372 persons killed and 10 002 injured. As many as 9909 buildings were destroyed and 7575 buildings partially damaged. The earthquake is the most thoroughly studied observed earthquake ever. Detailed information of the earthquake is available in a dedicated issue of the Bulletin of Seismological Society of America. /Teng et al, 2001/ The shaking during the earthquake was extremely strong. Two locations for free-field strong motion instruments experienced more than 1g of horizontal shaking and at several other locations more than 0.8 g. Figure 3-19 shows an intensity and peak ground acceleration map.

The earthquake generated surface rupture along approximately 96 km of the pre-existing Che-Lung-Pu fault /Lee et al, 2000/. The thrust fault dipped 25°–30° toward the east, with the hanging wall uplifted ranging from 1 m down the south and 9 m to the north. North of the Feng-yuan city, the surface rupture trended toward the northeast and crossed the Ta-chia-shi river, formed a waterfall of 8 m height, and destroyed a bridge, a water retention dam, and a major municipal water supply tunnel. The dam foundation was sheared and displaced by the rupture, creating a displacement of 7.8 m in the vertical direction, and 7 m in the northward horizontal direction.

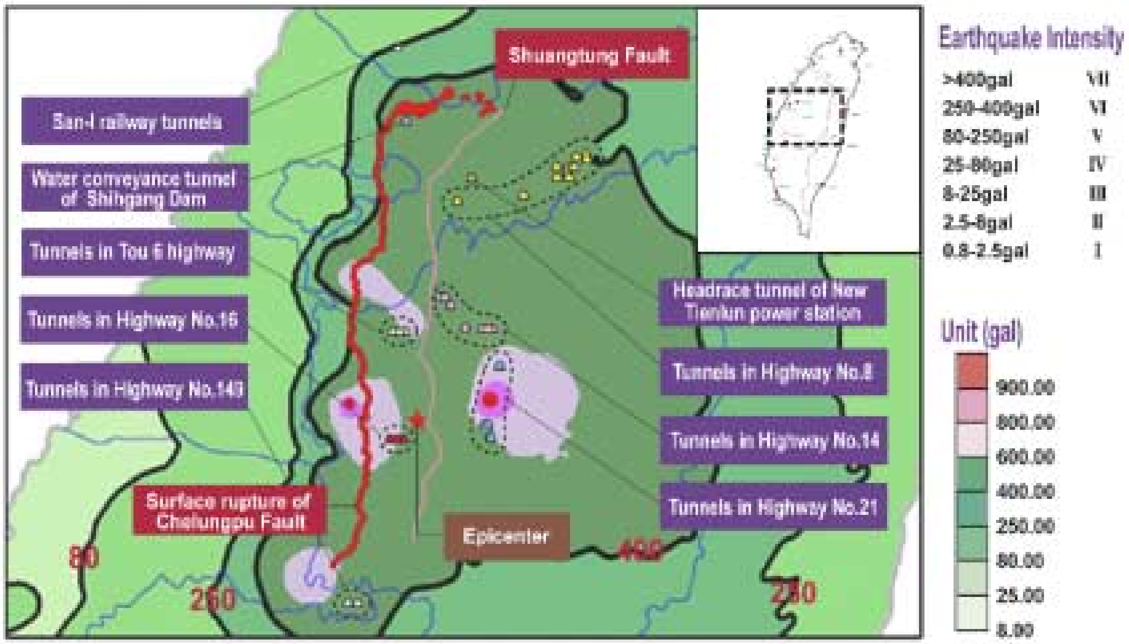


Figure 3-19. *The September 21, 1999 Chi-Chi Taiwan earthquake is the largest known onshore thrust-faulting event in the 20th century. The event caused damage to 49 tunnels out of the 57 that were investigated. The Shih-Gang Dam conveyance tunnel intersects the rupture fault and collapsed locally within a few meters of the 3–4 m displaced fault. The authors visited an adit to San-I railway tunnel and the Chi-Chi tunnels, c.f. locations at Highway No. 16 in the figure. These tunnels experienced more than 0.45 g in Peak Ground Acceleration so damage is to be expected, c.f. Figure 2-3. Intensity (Chinese Intensity Scale) and peak ground acceleration in gal (1 Galileo is 1* cm/s^2, *1000 gal is 10* m/s^2 *~1.02 g) at surface due to the Chi-Chi earthquake. Location of tunnels investigated for damage is also shown. The picture was kindly furnished by Mr T T Wang.*

Dr Ouyang at ERL/ITRI kindly furnished very valuable early information on the earthquake and effects on tunnels. The paper of /Wang et al, 2001/ was an overview of the damages caused in mountain tunnels, Table 3-5. It is important to note that the damage classification was based on functionality of the tunnels after the earthquake. Damage classification A is *No damage* or *Slight damage* (crack width < 3 mm, crack lengths < 5 m) where the tunnel can be used without any restrictions. Class B is *Moderate damage* with cracks > 3 mm, lengths > 5 m, liner fragments falling, liner steel exposed, constructions seams displaced and with accumulated seepages. These tunnels can still be used but with control. Class C is *Severe damage* where the use of the tunnel is prohibited without repair. Damage types are e.g. portal failure, cave-ins, pavement uplift or displacement, tunnel being flooded or where a tunnel shows damage on ventilation or lighting system.

The damaged tunnels are mostly located on the hanging wall of the fault and constructed in soft rock. The peak ground acceleration PGA is > 0.45 g in the area where most of the damaged tunnels are located, Figure 3-19, so damage is to be expected (c.f. Figure 2-3) Typical uniaxial compressive strength values for the sedimentary rocks are in the range of 20–30 MPa. Young's modulus is around 1 GPa. One of the tunnels, the Shih-Gang Dam Water Conveyance Tunnel was the only tunnel that intersected the Che-Lung-Pu fault. The tunnel was completely closed due to the 4m vertical and 3 m horizontal displacement that occurred, c.f. Figure 1-8.

The authors visited a ventilation and escape adit to the San-I tunnel, Figure 3-20, and also the Chi-Chi tunnels where damage was light and moderate. The authors found damage to the tunnels as expected. As the Peak Ground Acceleration exceeded 0.4 g, slight to moderate damage according to the definitions of /Dowding and Rozen, 1978/, was expected (c.f. also Figure 2-6 where the compilations of /Power et al, 1998/ show similar conclusions).

Table 3-5. Damages of mountain tunnels caused by the Chi-Chi earthquake. Tunnels located in the hanging wall of Che-Lung-Pu thrust fault were more damaged due to higher peak ground acceleration /After Wang et al, 2001/.

Location	No of tunnels assessed	Tunnel classification	Damage level	Tunnel(s) damaged	Damage in portals	Damage in mining section
Displaced fault zone	1	A	Slight	–	–	–
		B	Moderate	–	–	–
		C	Severe	1	–	1
Hanging wall area	50	A	Slight	26	32	35
		B	Moderate	111	9	8
		C	Severe	13	9	7
Footwall and other areas	6	A	Slight	2	3	2
		B	Moderate	–	–	–
		C	Severe	1	–	1

Figure 3-20. *The picture shows the concrete floor that was broken due to the Chi-Chi earthquake. The effects of shockwaves are slightly visible in the tunnel wall as the width of the water drain varies in width. One of the guides, Mr T T Wang, was member of the engineering team during construction and confirmed the existence of the shockwaves not being construction flaws. Photo: G Bäckblom.*

3.7 United States

Like Japan and Taiwan, the western US is heavily populated and also plagued by frequent and large earthquakes. The San Andreas fault in California is a world famous geological fault and described both in scientific papers and in best sellers. Strong earthquakes have occurred as the San Andreas Fault was reactivated, for instance the San Francisco earthquake (April 18, 1906; M_W=7.8) and the Loma Prieta earthquake (October 17, 1989).

The report by /Brown et al, 1981/ is particularly valuable since it deals with damage by displacements in tunnels. The study is mainly attributed to the behaviour of the Bay Area Rapid Transit Tunnel (BART) for a sequence of events but also gives particular information from Japan. Figure 3-21 depicts the location of tunnels discussed in this section.

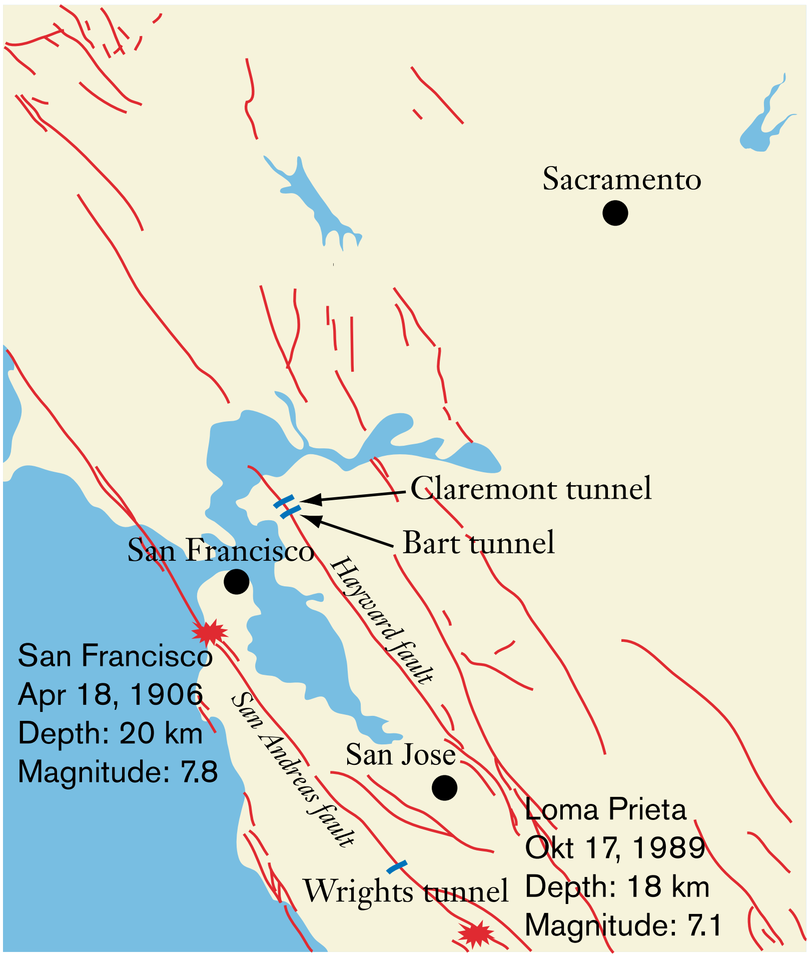


Figure 3-21. *Location of the Wrights tunnel, the BART tunnels, the Claremont tunnel and faults in the surroundings. Epicentres for the San Francisco 1906 earthquake and the Loma Prieta 1989 earthquake are shown.*

The San Francisco earthquake devastated much on the surface, but the damage to tunnels were small. Associated to the earthquake, a right-lateral displacement of 1.7–1.8 m occurred along the San Andreas shear zone intersecting the Wrights tunnel about 120 m from the northeast portal. Damage in the vicinity of the maximum offset included crushing of timber supports, heaving of rails, and rock fall. Some railroad ties were broken. Previous measurements of displacements along the tunnel were recently re-evaluated /Prentice and Ponti, 1997/. The new estimate is that faulting was confined to a zone less than 400 m wide and that 60–85% of the co-seismic slip occurred along a single fault plane, Figure 3-22. 15–40% of the offset is distributed within a few hundred meters of the principal fault plane. This is in contrast to the historic records suggesting a 1.5 km broad zone of faulting. The deformations recorded off the fault could either be construction flaws, results of shockwaves or true fault displacements in the tunnel.

At the Kern County, M=7.7 earthquake, three tunnels were seriously damaged. The epicentral distance was 47 km. The tunnels have limited cover (15–75 m) and are close to the side of the valley. In one of the tunnels (cover 38 m) a 1.22 m displacement were found, while there was a fracture with practically no vertical offset directly above the tunnel /Brown et al, 1981/.

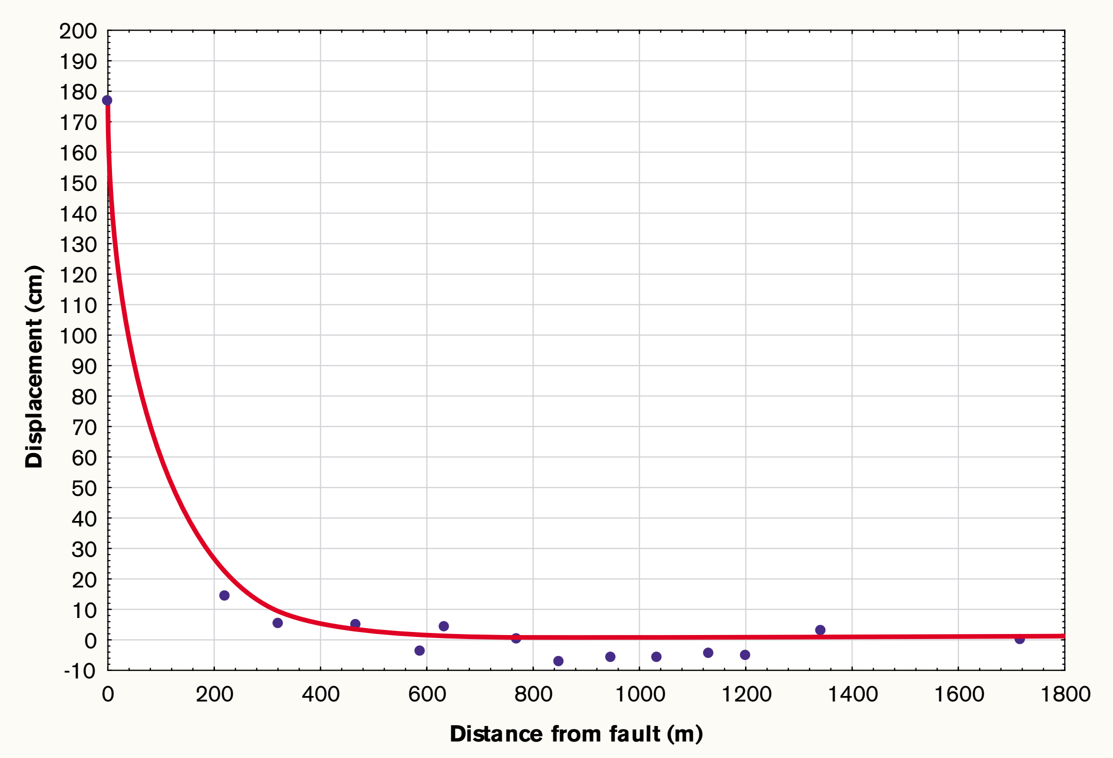


Figure 3-22. *The Wrights tunnel built in the late 19th century intersects the San Andreas Fault. The figure shows the transversal deformations along the tunnel assuming that the tunnel axis between the portals originally was straight /Revised after Prentice and Ponti, 1997/.*

The San Fernando earthquake of M=6.6 in 1971 caused the Santa Susana thrust fault to be further displaced. The fault crosses the Balboa inlet tunnel about 300 m from the portal, epicentral distance 16 km. The reinforced concrete liner spalled along a 90 m section at the fault crossing and longitudinally cracked the liner for some 300 m on each side of the fault. The tunnel was under construction in sedimentary rock when the earthquake hit. The overburden is around 5m.

The Loma Prieta earthquake (Figure 3-21) caused severe damage on the surface. While most of the other major transportation systems of the area were paralysed, Bay Area Rapid Transit Tunnel (BART) became the only means of public transportation for many people in the Bay Area. The system was unscathed by incorporation of stringent seismic criteria for the design and construction of BART more than 30 years ago. The Loma Prieta earthquake was the first major earthquake along the San Andreas Fault since the San Francisco 1906 earthquake. The average strike-slip displacement was 1.2 meters while the average reverse-slip displacement was 1.6 meters. No distinct surface faulting occurred and perhaps because this earthquake was unusually deep as compared to other earthquakes in California.

On Sunday June 28, 1992, the most powerful US earthquake in 40 years rumbled through Southern California. It was the largest earthquake in California since 1952 and the second largest since 1906. The Richter magnitude M=7.4 tremor was centred near the small desert community of Landers. Numerous significant aftershocks followed the event. At 8:04 a.m. a second (M6.5) earthquake, centred near Big Bear Lake in the San Bernardino Mountains, struck approximately 30 km west of the initial shock. The two events caused one fatality, over 400 injuries, and around $100 million in damage to property, roads and water systems. No damage to underground facilities has yet been reported.

The /Brown et al, 1981/ report focussed on damages due to displacements. Their report describes in detail the BART tunnels excavated through the Hayward Fault. The locations of the BART tunnels and the Claremont tunnel are depicted in Figure 3-21. The tunnels cut through sequences of rocks of sedimentary and volcanic origin, partly in squeezing ground with an overburden of 10–80 m. The most important structure in the area is the Hayward fault zone. The zone is at least 80 km long and essentially vertical. Surface ruptures due to earthquakes have occurred several times in the past. In the period January 1969 to January 1980 approximately 188 earthquakes were recorded within 15 km of the BART tunnels with magnitudes from 0.35 to 3.38. The slippage rate is in the order of 6–8 mm/year. The construction of the BART tunnels took place from 1965 to 1968 with the most difficult squeezing ground at the Hayward Fault Zone and other fault zones. The design did not account for the slip rate at the Hayward Fault and the tunnels were later somewhat re-designed. Data from the fault really shows that slippage is confined to the close surrounding to the fault, Figure 3-23.

Close to the Yucca Mountain, a magnitude 5.6 earthquake, focal depth 9 km, struck in June 29, 1992. The epicentre was within 20 km of the potential site for the US high-level waste. The so-called X-tunnel is located 3 km from the epicentre, mined in welded tuff and with an overburden of up to 125 m. No damage was found in the tunnel /Voegele, 2001/. The acceleration in the tunnel was estimated to 0.15 g /Savino et al, 2001/.

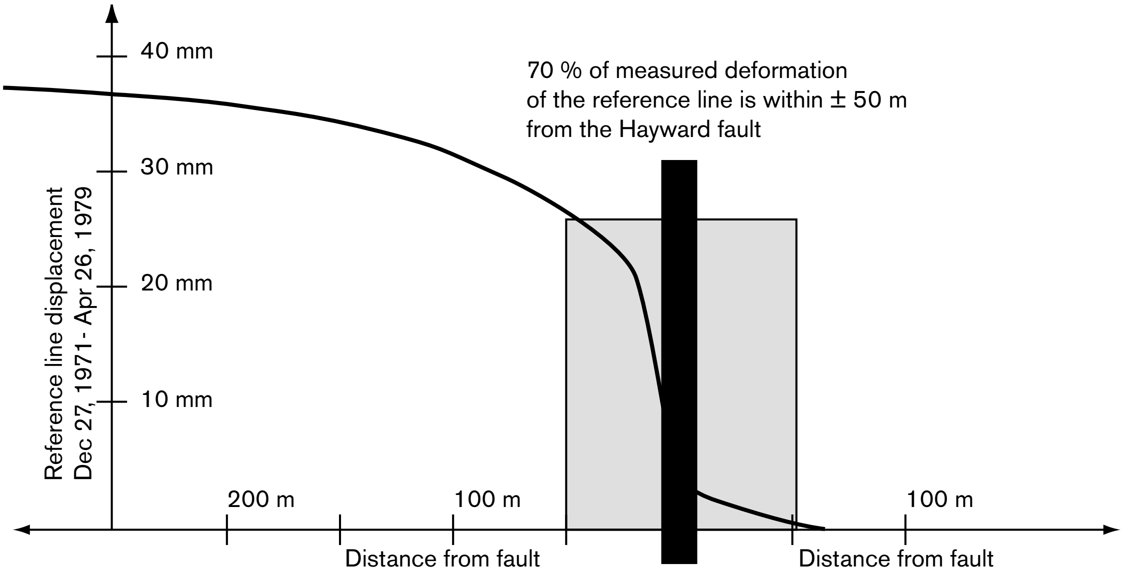


Figure 3-23. *The graph shows the displacement over the Hayward fault zone over a period of more than 7 years. Data from the C1 tunnel /Revised after Brown et al, 1981/.*

3.8 Former Yugoslavia

A case of tectonic disturbances has been reported from a tunnel in former Yugoslavia, /Obradovic, 1990/. (The paper does not pinpoint the location of the tunnel so it can not be located on an actual country map). The type of problem was similar to the BART tunnels described in the previous section. In 1987 a visible and continuous crack was recorded across the tunnel alignment at the pumped storage tunnel scheme in the middle of the former Yugoslavian territory. It was concluded that this damage was due to neotectonic upheaval at a block boundary crossed by the tunnel

3.9 General conclusions from the case studies based on measurements and/or field evidences

The case histories provide strong evidences that damage is much less underground than at surface.

Even for tunnels constructed in very soft rock, damage due to shaking hardly ever occurs for acceleration below 0.2 g (2.0 m/s^2). When medium to severe damage occur for higher accelerations, such damage is typically confined to the vicinity of fracture zones that may or not may have been reactivated as a consequence of the earthquake. Table 3-6 lists cases where data on displacements close to the faults have been reported. Even for very strong earthquakes, deformations are confined to a few hundred meters from the re-activated fault.

Table 3-6. Overview of measured displacements, observations close to re-activated faults.

Tunnel	Fault Length	Deformations, Observations
Tanna, Japan	24 km surface rupture	Deformations closely related to the faults. Main tunnel wall not damaged in spite of being 0.5 m from the active shear zone.
Inatori, Japan	18 km main fault and a 3 km subsidiary surface fault cut by the tunnel	0.5–0.7 m displacement within a zone of 20 m. Deformations as measured on the lining, show kinks in the order of decimetres 300–400 metres from the fault. It is not known if these deformations are due to faulting.
Shioya-Danigawa, Japan	5 km in length	8-cm lateral and 5-cm vertical relative displacement of the lining confined within a 10 m long zone around the fault crossing.
Tottori, Japan	A disguised active fault displaced. Zone width is 7–10 m	Damage in concrete lining is limited to a few metres from the fault that moved. The headrace tunnel was left-laterally displaced 0.1–0.2 m.
Mathjabeng mine, South Africa	50 km long fault	Damage and new fracturing in the rock within 30 m of the fault that displaced ~0.4 m* (* Slip-value is uncertain).
A.R.M, Shaft #5, South Africa	5 km long fault	Damage to the rock (except rock fall and tunnel closures) within some 10 m from the fault that displaced ~0.2 m (study in progress).
Shih-Gang Dam Tunnel, Taiwan	96 km of surface rupture	Damage to concrete are confined to within a few metres from the fault, that displaced the tunnel 4 m vertically and 3 m horizontally.
BART tunnels, USA	> 80 km long	Fault creep restricted to a zone < 250 m from the fault. It is not known if there are very minor zones accommodating these displacements.
Wrights tunnel, USA	San Andreas Fault, Total length ~1200 km, rupture length year 1906 ~430 km	60–85% of the co-seismic slip at the San Francisco 1906 earthquake occurred along a single fault plane. 15–40% of the offset is distributed within a few hundred meters of the principal fault plane.

4 Existing data, experiments and analyses to assess the earthquake effects on the deep geological repository

Chapters 2 and 3 are focussed on the field evidences of earthquake damage to underground facilities in general. This chapter details the description of the functions of the deep repository after its closure. The field data (from Chapter 2 and Chapter 3) are here combined with reported analytical, numerical and experimental studies to broaden the knowledge base before assessment of the potential influence of earthquakes on the safety-related functions of the repository. The discussion here is by no means complete, but should reflect recent achievements on important issues.

The general design requirements imposed by the Swedish Nuclear Inspectorate (SKI) are:

- Safety should be maintained by a passive barrier system.
- Deficiency in one barrier function must not obviously impair the repository safety.

Barrier function is the ability of the barrier to isolate or retard the dispersion of radioactive matters, directly or indirectly.

SKB makes use of a multi-barrier concept where the hazardous spent fuel is sealed in a water- and gas-tight copper/steel canister. Buffer surrounds the canister. While the buffer is made of low-permeable clay, the chemical impact by groundwater is very small. The buffer also makes it possible to accommodate displacements in the rock without damaging the canister. The buffer and canister are emplaced in a rock formation at considerable depth 400–700 m below the surface to decrease risk of unintentional intrusion into the repository and also to achieve favourable chemistry in the deep rock formations, i.e. that is there is no free oxygen at hand.

The radioactive decay in the spent fuel (and naturally occurring Uranium in the granitic bedrock) produces heat. The repository will be designed so that the temperature is below 100°C at the canister surface. The canister shall be tight and have the mechanical strength to withstand anticipated forces that may act on the canister, even during glaciation when the ice sheet over the repository could be up to 3 km. Expected loads e.g. during a glaciation may add up to ~45 MPa extra load on the canister /SKB, 1999c/.

The canister is thought to be damaged if it experience displacements > 0.1 m, Figure 4-1. In case of canister tilting, it might be possible that fractures can displace around 0.4 m without damaging the canister /Börgesson, 1992/. However, there is also a possibility that the fracture displacement is fast. In this case it might be possible that the canister and the buffer acts like a solid body. The conservative approach is then to assume that any fracture displacement > 0.1 m may cause a canister shearing deformation of 0.1 m. SKB assumes that the accumulated fracture displacements due to earthquakes or other reasons should be less than 0.1 m not to damage the canister.

It may also be shaking due to earthquakes could damage the integrated function of the canister and buffer. To promote isolation and the slow retardation, the buffer should be in good contact with the buffer and the canister.

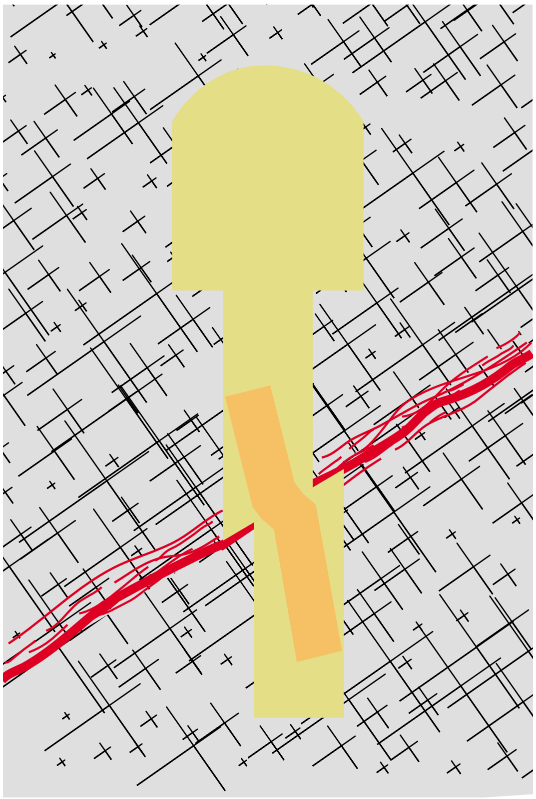


Figure 4-1. *Sketch showing a possible canister breakage due to fracture slip.*

Thus from a repository point of view the following issues are of particular relevance:

- Can earthquakes influence the performance of the canister due to load increase?
- Can earthquakes create new fractures in the rock surrounding the canister?
- Can earthquakes displace discontinuities intersecting a canister hole by more than an accumulated 0.1 m?
- Can earthquakes generate groundwater overpressures so that the effective stresses drops significantly?
- Can earthquakes damage the buffer due to rapid changes of water pressures caused by?
- Can earthquakes significantly impair the good contact between the canister and the buffer and between the buffer and the rock?
- How can existing experience from earthquake impact on underground openings be transferred to the peculiar situation when strong earthquakes may be generated as a consequence of rapid deglaciation in the future?

4.1 Load increase due to earthquakes

The static load on the canister is assumed by SKB to be the sum of the swelling pressure of the buffer plus the water pressures added on the outside of the canister. The possibility that the host rock will be so highly pressurised that the engineered barriers are squeezed is not likely to occur for hard rocks (see pages D-25ff in /JNC, 2000/). JNC has evaluated the conditions at a depth of 1000 m where primary rock stresses are around 27 MPa in vertical and horizontal direction and presuming that the counter-pressure from the buffer is very low. The impact of short-term earthquake effects is not likely to initiate viscoelastoplastic rock creep of the rock material itself.

The dynamic influence of earthquake will however provide small stress increases, both due to the shaking, but also due to the excess groundwater pressure that may be generated. Assuming that seismic wavelengths are long as compared to the diameter of the tunnel, the seismic stresses can be approximated as a plane wave. For such waves the compressive and shear stress increase is related to particle velocity.

Using Canadian data for the Canadian Shield and attenuation relations for the Canadian Shield, the maximum compressive and shear stresses will be around 4 MPa and 1 MPa respectively for an earthquake of Richter magnitude 6 at a distance of 40 km from the repository /Ates et al, 1995/.

Using Scandinavian attenuation according to /Wahlström and Grünthal, 2000b/ and the data by /Ates et al, 1995/ we arrive at the seismic stresses 4 MPa and 1 MPa (PGA=0.1 g) when being at a hypocentral distance of 7 km for a magnitude M_L=6 earthquake.

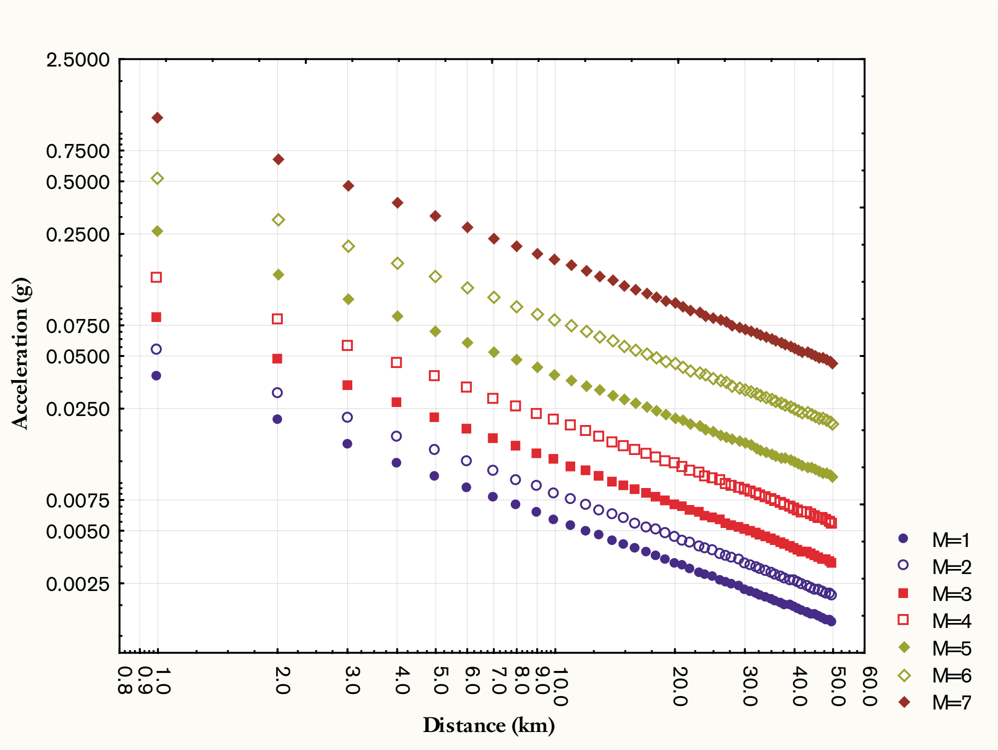


Figure 4-2. Peak Ground Acceleration (1 g=9.81 m/s^2) as related to magnitude and distance to hypocenter by application of Scandinavian empirical attenuation based on work by /Wahlström and Grünthal, 2000b/. The equations are described in Appendix A1.3.

Another factor to consider is the possible increase in water pressure due to earthquakes; the displacement of a fault will create transient and/or permanent stress changes in the bedrock that may influence the water table. There is an abundance of papers on water level changes due to earthquakes, both transient and stationary /e.g. Akao, 1995; Hsiung et al, 1991; Ishimaru and Shimizu, 1997; King et al, 1995; Rojsraczer et al, 1995; Sun et al, 1998/.

Of particular interest is the paper by /Muir-Wood and King, 1993/ where the authors concluded that the hydrological effects of earthquakes are determined by the style of the fault displacement, rather than simply the size of the earthquake. The conclusions are based on several field evidences coupled with modelling of co-seismic strain that gives consistent results with the field data. Events that involve a significant normal faulting component expel substantial quantities of water, whereas reverse faulting do not. Strike-slip events typically also expel water in more restricted regions, but not in the quantities associated with normal faulting events. They also conclude that increases in spring and river discharges peak a few days after the earthquake and typically excess flow is sustained for a period of 6–12 months in case of normal faulting. In contrast, hydrological changes accompanying pure reverse fault earthquakes are either undetected or indicate lowering of well levels and spring flows. The rise and decay times of the discharge are shown to be critically dependent on fracture widths.

The paper by /Akao, 1995/ merits further explanations. The approximation suggested by Akao is that the maximum value of water-table change would be approximately one hundred times the slip displacement as calculated from the dislocation theory. Thus 1m of slip will at maximum produce 100 m of water level changes (1 MPa) and 10 m of slip water level changes of 10 MPa. A discussion with scientists (e.g. Prof. Watanabe, Saitama University, pers. comm.) does not rule out the conclusions of Akao.

4.2 Can new fractures be created?

The main hypothesis forwarded by SKB and several scientists is that release of energy is dominated by shaking and by displacements along pre-existing faults and fractures, rather than by the creation of new fractures. The second hypothesis is that the fault displacements may have an impact on the rock in close vicinity of the fault and SKB therefore defines a setback zone – "a respect distance" from the fault where no canisters will be deposited.

This study has been focussed on effects of fault slip rather than effects due to shaking. The records collected from tunnels intersecting faults that displaces due to earthquakes showed that damage is localised to the proximity to the fault, Table 3-6. Damage in concrete linings was often within 5–10 m from the fault that moved, evidencing that the effects of faulting would be extremely local in nature. One of the very few records collected showing damage in the rock itself is interesting as the data is from highly competent, strong rock. The data from South Africa data showed that damages and new fractures were developed within ~30 m of a fault that displaced ~0.4 m and generated a magnitude 5.2 earthquake /Dor et al, 2001/. It can be expected that if new fractures were created, these would be located in the immediate vicinity of the fault. Studies on post-glacial studies support this general conclusion. Examinations of the 50 km long post-glacial fault set in Lansjärv /Bäckblom and Stanfors, 1989/ showed that new fractures at the surface appears to be confined within a few metres from the scarp.

The work by /Ortlepp, 2001b/ suggested that absence of faults and fractures is a less favourable factor in high-stress regimes. The mining-induced fracturing occurred at very high stresses in very good rock quality where there are no faults or fractures that could accommodate the stress build-up.

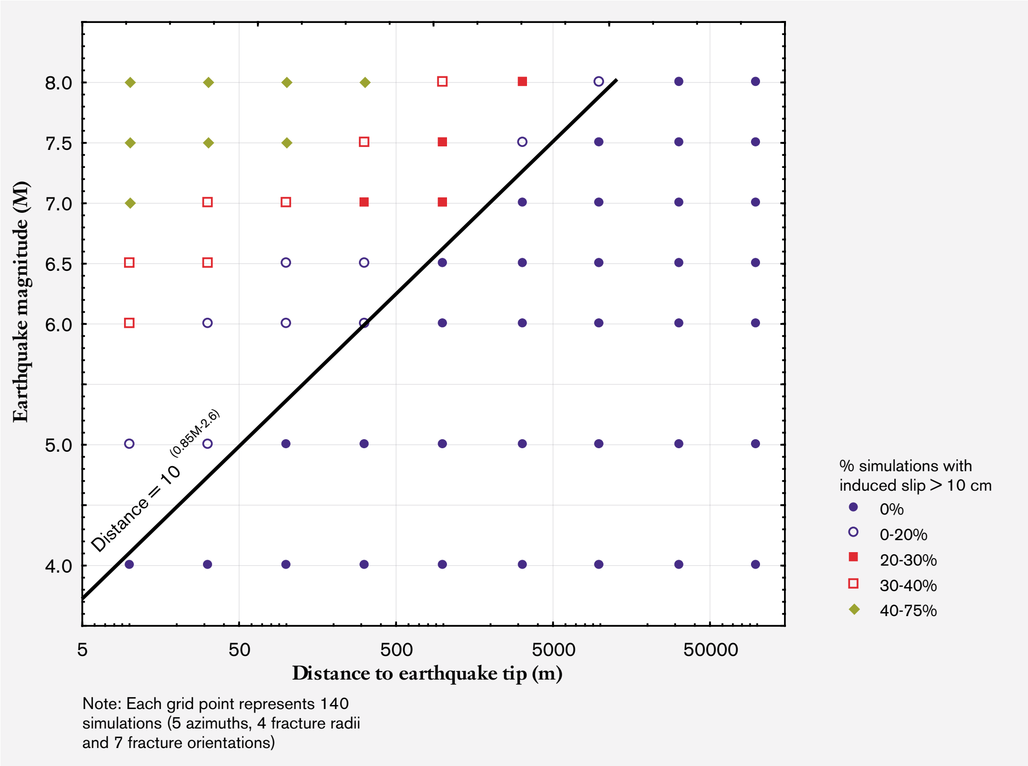
4.3 Accumulated displacement of fractures by more than an 0.1 m at the location of canisters

The canisters will be deposited in positions in the rock sufficiently far from faults so that any secondary accumulated fracture displacement will be less than 0.1m due to the slip on the main fault.

The deformation data collected along the tunnels intersected by faults and described in Chapter 3, showed that the major displacement is at the location of the fault and that deformation rapidly decreased with increasing distance from the fault. There is uncertainty concerning the magnitudes of deformation. Deformations measured in the tunnels do not necessarily indicate slip along secondary faults or fractures for the following reasons: Measurements were performed on the tunnel lining or on rails along the tunnel, not on the rock itself. It may be that the lining and/or rail were de-coupled from the rock. A second problem is that the earthquake generates shockwaves in the tunnel walls; the measurements of deformation from a certain distance (c.f. measurements in the Inatori tunnel, Chapter 3.3.2 and the Wrights tunnel, Chapter 3.7) include these possible shockwave effects.

Numerical models are also useful to understand the potential for displacements > 0.1 m over the deposition hole for the canister. SKB has executed two types of models. The first type of model used by SKB (a boundary element program) is based on the assumption that a reactivation of a fault cause displacements in a fractured rock mass, assuming that there is no friction along the fracture planes, /LaPointe and Caldouhos, 1999; LaPointe et al, 1997/. The main results based on hundreds of simulations (Figure 4-3) showed that no fractures were displaced more than 0.1 m if they were located more than 3 km from a magnitude 7 earthquake (Fault length > 45 km). However, in the simulations large fractures were permitted to intersect canister positions, which will not be accepted in a practice. In fact, no displacement exceeding 0.1 m could be demonstrated, in the simulations, on target fractures with radii less than 100 m. Since all tunnels and canister holes will be mapped in detail, we consider it unlikely that such large fractures will not be detected during mapping. If considerations are made for large fractures cutting canister positions, the curve on Figure 4-3 should be shifted vertically at least one earthquake magnitude (Munier, unpublished data). As a consequence, the distance from an earthquake of magnitude 7, which can trigger secondary slip exceeding 0.1 m, decreases to about 1 km or less.

The assumption that there is no friction in the fractures is thought to be very conservative but has some merits as it involves the improbable case that there is local, complete friction-loss in the fractures due to high and rapid water-level changes caused by the earthquake. The described model approach of /LaPointe et al, 2000/ is static and do not account for the dynamic, shaking effects. Further, it does not fully take into consideration the accumulated slip on target fractures; since reliable estimates of postglacial earthquake frequencies and magnitudes were not available, the present seismicity was used to demonstrate a probabilistic application of the result. SKB therefore has initiated a study to obtain an estimate of the seismic activity during the latest glaciation. This will be used



Note: Each grid point represents 140 simulations (5 azimuths, 4 fracture radii and 7 fracture orientations)

Figure 4-3. *The diagram is based on fracture data from the three Swedish study sites (Aberg, Beberg and Ceberg, /Revised after LaPointe et al, 2000/). Each point in the diagram show how many percent of each realisation yielded slip that exceeded 0.1 m. Each point in the diagram is based on 140 simulations.*

as input for updated probabilistic calculations. Nevertheless, the probabilities calculated by /LaPointe et al, 2000/ were extremely low. It is estimated that the probability of accumulated net slip on target fractures will still be very low in spite the fact that the seismic activity used as input will be increased considerably.

The second type of models used by SKB is an explicit finite difference program /Christianson, 2001/. In this work, an earthquake of M=6 is modelled. The effects on a horizontal fracture with area 200 m·200 m at a depth of 400 m below the surface are studied. The study also evaluated the effects of varying fracture friction properties. In Figure 4-4 it is shown that the displacement for a magnitude 6 event is less than 8 cm at a distance of 200 m from the fault for the zero friction angle fracture. Significant displacements (> 1 cm) could only be demonstrated for zero friction or low strength cases at distances less than 1 km.

Comparison of the static and dynamic modelling approaches does not provide any substantial difference in results. Close to faults (< 2 km), the static effects seem to overshadow the dynamic effects.

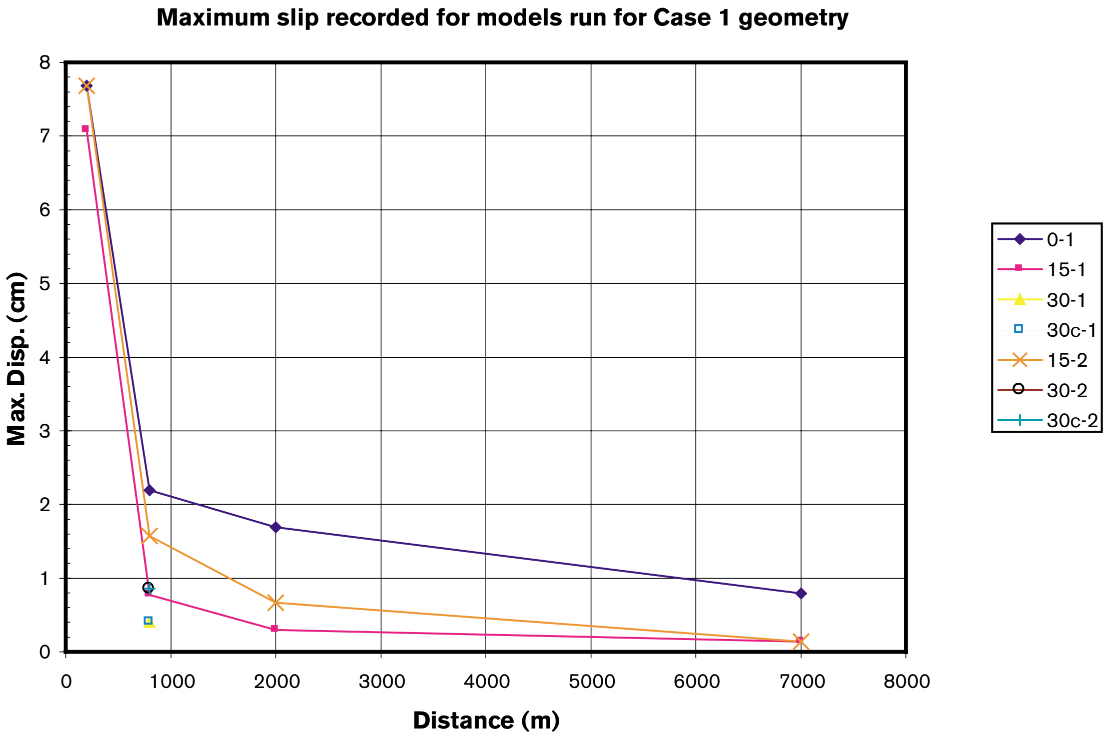


Figure 4-4. *Variation of maximum relative displacement (cm) with distance (m). The symbols are named according to the convention 'x-y' where x is the angle of friction and y is the stress state. Stress state 1;* σ_1*_horizontal 35 MPa,* σs_2*_horizontal 20 MPa,* σs_3*_vertical 13 MPa: Stress state 2;* σ_1*_horizontal 55 MPa,* σ_2*_horizontal 20 MPa,* σs_3*_vertical 7 MPa: 'c' signifies cohesion included (1 MPa) /After Christianson, 2001/.*

4.4 Creation of groundwater overpressure that may cause complete friction-loss in the rock

The occurrence of earthquakes creates permanent stress changes in the rock. The sudden displacements may also cause transient water-level changes. Near the Chi-Chi earthquake, 8 m high water fountains were observed (T T Wang pers. comm.) In soft sediments these transients can cause liquefaction, i.e. the state where the water pressures exceed the grain pressure and the soil-like materials completely looses strength and behaves like "quicksand". An important question is if there is an analogy in hard rock. Fault displacement may cause a compression of the rock mass thereby increasing the pore pressure. The sudden increase of water pressure reduces the normal stress within the rock while not changing the shear stress i.e., a sufficiently strong increase in water pressure could considerably lower friction thereby triggering fault slip.

We were, however, in this study unable to find field data supporting friction-loss in subsidiary faults and fractures due to earthquakes. Yet, papers on earthquakes triggered by injection of water during oil and gas production, geothermal production or during construction of dams and reservoirs have been studied to shed light on this issue. The mechanisms of man-made earthquakes appear to be well understood. The rare earthquakes caused by reservoir filling are explained as follows: at the filling of the reservoir, the rock is compacted and pore volume is decreased, thereby causing higher pore pressure. The man-made increase in pore pressure is far slower (months, years) as compared to earthquakes. It dissipates down into the bedrock where the effective stress in the fracture is reduced. In the scientific field of man-made earthquakes, there is still a controversy if one of the most famous events, the 11th December 1967 M=6.3 earthquake at the Koyna Dam (India) was man-made or not /Bapat, 1999/.

As described in the previous section, one of the SKB models /LaPointe et al, 2000/ is very conservative in assuming that all fractures in the fracture network possess no friction whatsoever. The model in this respect accounts for complete friction-loss due to rapid water level changes whether this effect exists or not in the rock. Clearly, further research and modeling will increase our understanding of this issue.

4.5 Potential damage to buffer due to rapid changes of water pressures

Rapid changes of water pressures could cause potential damage to the repository should the buffer liquefy. The liquefaction of the buffer turns the material from a solid state into a liquid state that could create a risk that the canisters tilt or sink. SKB has in a previous report /Pusch, 2000/ treated this issue with the conclusion that the necessary prerequisite for liquefaction of buffer exist, but that the density of buffer and stress conditions practically eliminate the risk for liquefaction assuming earthquakes up to magnitude 7–8 with normal duration time. Further, the SKB design with saturated buffer density ~2000 kg/m^3 well exceeds the critical density (1700–1800 kg/m^3).

Similarly, /JNC, 2000/ studied seismic stability of the engineered barriers during an earthquake. Engineering-scale models (Scale 1:10 and 1:5) of the canister and the buffer were shaken according to a well-defined earthquake spectrum to verify and validate advanced numerical values. In a numerical model accounting for porewater pressure in the buffer, no rise of porewater pressure in the buffer material could be demonstrated, and the possibility of liquefaction in the buffer was considered remote.

4.6 Potential loss of integrated function canister–buffer–rock

The experiments by Japan Nuclear Cycle Development Institute /JNC, 2000/ also studied the influence of the integrated function of the canister and the buffer during a well-defined earthquake. Two issues were adressed. a) the canister must not move significantly within the Engineered Barrier System (EBS) and b) the buffer must not reach a shear failure condition due to stresses caused by an earthquake. Each measuring point showed almost the same values of time-dependent acceleration as those of the input seismic acceleration for both the case when the buffer is dry and when the buffer is fully saturated. The overall conslusion is thus that the engineered barrier system behaves as a rigid body.

The JNC EBS-design does, however, not exactly match the SKB design; the properties of canister and buffer are different in details. The SKB design uses higher density for the buffer (2000 kg/m^3 as compared to 1800 kg/m^3 used in Japan) and the thickness of the buffer is also less (0.35 m as compared to 0.70 m). The JNC-conclusion that the EBS acts as a rigid body has not been verified by similar SKB-studies, but it is anticipated that the Swedish system will not differ significantly in this aspect.

4.7 Can present-day experience be transferred to the situation that may prevail at the state of rapid deglaciation in the future?

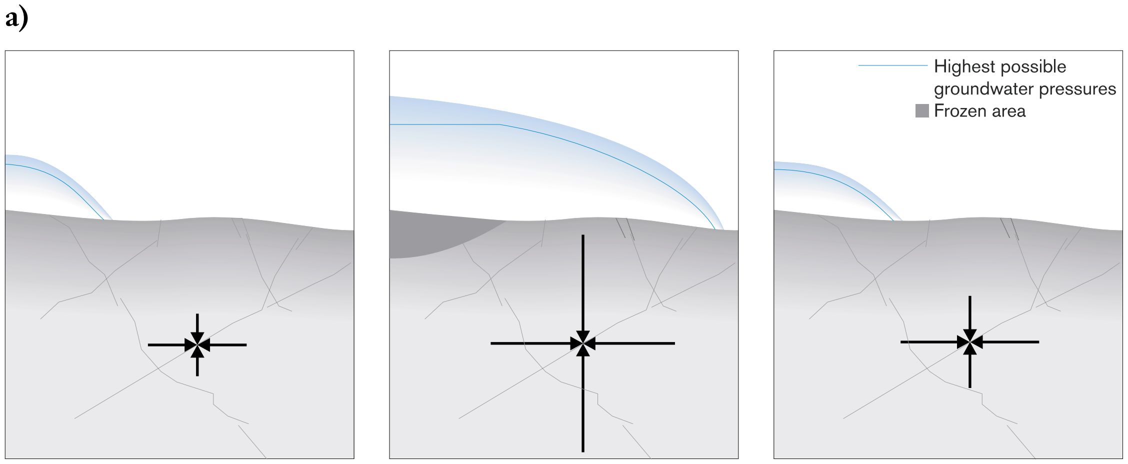
- Historical records suggest that Sweden experienced large single-events fault slips at the latest deglaciation around 9000 years ago. Most, if not all post-glacial movement took place along zones shattered and chemically altered long before pre-quaternary times /Bäckblom and Stanfors, 1989/. The overall mechanical and hydro-mechanical situation is different from any present-day geological situation, Figure 4-5.
- Loading by ice sheets allows the build-up of tectonic stresses. Deglaciation leads to release of stored energy. At the last glaciation, the geoid was down-warped 800–900 m at the maximum /Boulton et al, 2001/. The rapid melting caused very high uplift-rates, /Påsse, 2001/, where uplift was around 35 mm/year down to present-day maximum 9 mm/year, The rapid uplift is anomalous to present-day situation.
- The hydrological situation at the ice-front is very dependent on the basal conditions of the ice sheet. The most conservative approach is to assume that full hydrostatic pressure may be developed that decreases the normal pressure and facilitate faulting. The situation, with a rapidly melting ice cap, is anomalous and not found anywhere on earth today.
- Most experience from earthquake effects on underground facilities emanate from plate boundaries where strike-slip fault displacements dominate. Though significant strike slip components can be demonstrated on postglacial faults, the reverse faulting component appears to dominate.

The high uplift rates caused changes in the virgin stress situation. The expected effect is increase of horizontal stresses (due to uplift of the down-warped geoid) if plane strain boundary conditions applies. If not, no specific increase of horizontal stresses should develop. In any case, there is a rapid decrease of vertical stresses due to the diminishing ice cap. These changes of primary stresses may trigger the reactivation of faults. However, in case reactivation/faulting occur, we must readdress the critical issues:

- Can new, significant fractures be created?
- Will accumulated displacements > 0.1 m occur in the rock where the canisters are deposited?
- Will post-glacial earthquakes behave like the earthquakes we can study today?

As argued earlier, it is unlikely that substantial new fracturing develops. This is evident from the tunnel data collected in this report, but also from the previous post-glacial studies in Sweden. We find it reasonable to assume that "glaciation-induced" earthquakes, once triggered, should not significantly differ from any "mining-induced" or "natural" earthquake and therefore, many general and empirical relations should apply.

The second issue is the hydro-mechanical anomaly at the ice-front. It is expected that no relevant field data can be collected so reasoning is circumstantial. The decrease in normal pressure should cause less potential to store mechanical energy before faulting. /Lindblom, 1997/ argued that hydraulic jacking could reach down around 60 m below surface when the ice front is 1 km high. Assuming that ice crevasses are open and completely water-filled, jacking can reach 800 m of depth for a 1 km high close-by ice front. In case slip occurs it is expected that faults be reactivated rather than new faults created.



Before the ice sheet reaches the site, the horizontal stresses dominate.

When an ice sheet of great thickness overlies the site we can expect a surplus of vertical stresses.

After the ice has melted away, the vertical stresses are relieved faster than the horizontal stresses, which can cause horizontal and gently-dipping fractures to widen.

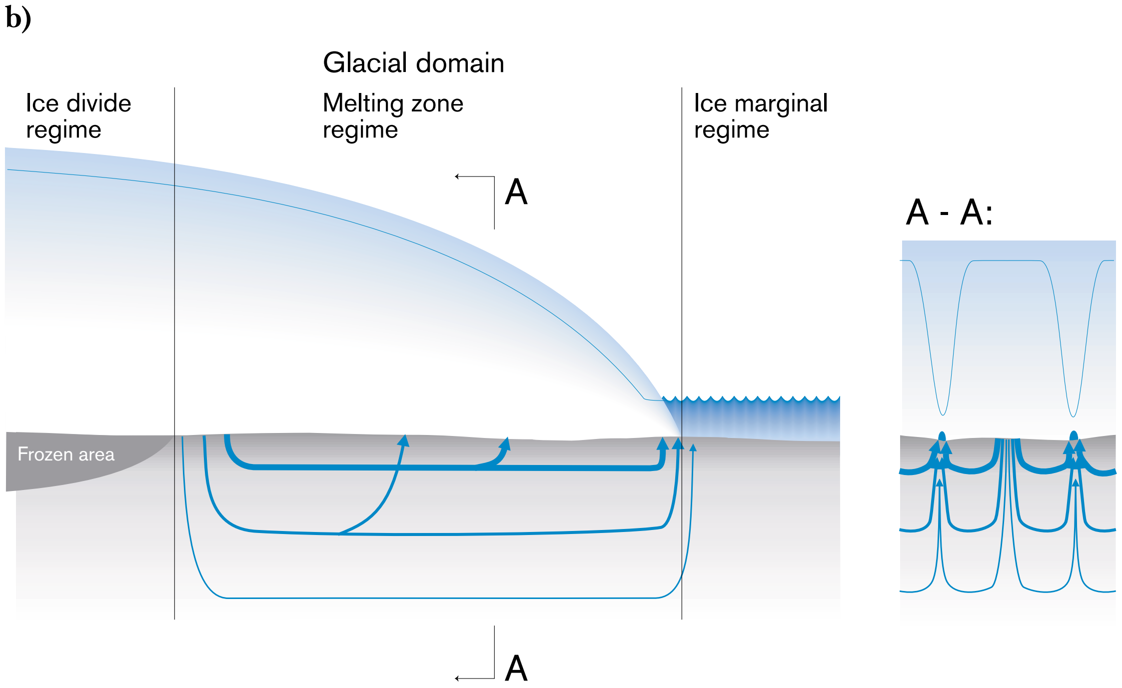


Figure 4-5. *a) Rock stress situation during a sequence of glacial advance and retread. b) The boundary conditions for groundwater flow are determined by the presence of the ice /After Boulton et al, 2001/.*

It is also expected that potential slip occur where no canisters are deposited as they are deposited in the rock volumes at a distance from faults. It is also expected that any oxygenated water that penetrates into the bedrock will be reduced. The investigations e.g. at the Lansjärv post-glacial fault study supports these conclusions, /Bäckblom and Stanfors, 1989/.

The third issue relates to the fault slip-mechanism. /Wells and Coppersmith, 1993/ concluded that slip-type is insignificant for many empirical relations but for the reverse faulting. Data from reverse faulting /Wells and Coppersmith, 1994/ are however much more scarce (only four data points!) than for other fault mechanisms and their conclusion might be revised at more data. It appears that reverse faultings have created magnitudes around 6.5 for all the data points and it is not possible to conclude whether or not the reverse faultings are significantly different from other slip-types. Experience from the Chi-Chi earthquake in Taiwan (thrust faulting) shows that shaking was much more severe at the hanging wall than at the footwall. It is true that different slip-types will create different response spectrums, but as SKB is not concerned with the pre-closure period this would not matter.

Mapping and dating of fracture movements is a good tool to shed light on matters of displacements over the canister positions in a future post-glacial, environment. Dating of fracture movements can either use markers, like displacements of the quaternary sediments or e.g. the electron-spin resonance methods /Ikeya, 1993/. In the crystalline bedrock it is difficult to find good markers. However some parts of Sweden is still covered by sediments (lithified). Careful studies at the island of Öland /Milnes and Gee, 1992/ of fractures 10–100 m in length showed that the maximal displacement over a period of 450 million years is about 0.1 m. The deformation accumulated on far more than one glaciation and of course include some tectonic component.

In summary: Data acquired from current earthquakes and its effects are considered relevant in many aspects. The physical laws of energy dissipation from earthquakes are considered valid. Damage effects on the rock are basically governed by the magnitude and distance from the seismic event.

4.8 Miscellaneous issues relating to the repository

In the following several issues are treated that relates to seismic stability and repositories.

4.8.1 Can the repository itself induce earthquakes?

Section 4.5 discusses methods to trigger earthquake by man-made actions. The repository can be treated as a room-and-pillar-mine. The question is: Can the repository itself induce earthquakes? This question has been addressed by Atomic Energy Canada Limited, /Martin and Chandler, 1996/ where the extraction ratio of the repository was compared to extraction ratio in deep Canadian mines. Martin and Chandler concluded that seismic events and associated damage caused by deep mining (> 1 km depth), will not be encountered in a repository between a depth of 500 m to 1000 m. The major difference between the mine and the repository is the low extraction rate for the repository (0.25–0.30) as compared to the mine.

4.8.2 Can shaking induced by earthquakes before closure damage the repository?

Damage to underground facilities occurs, by empirical knowledge, when the Peak Ground Acceleration is greater than about 2 m/s^2. Taken the Scandinavian data this is a very unlikely scenario. Figure 4-6 shows all historical earthquakes M > 4 since the 17th century. The potential Swedish sites are statistically below 0.15 m/s^2 (10% of exceedance in a 50 year period, Figure 1-6).

Some countries, like Japan and USA, must consider present-day seismicity in the pre-closure operation stage. The present US repository concept does not include backfilling of the tunnel system, and the matter of shaking and possible rock falls will therefore have to be addressed over the lifetime of the repository.

There are many papers and reports that address this question and other miscellaneous design questions /Ates et al, 1995; Ceylan et al, 1995/.

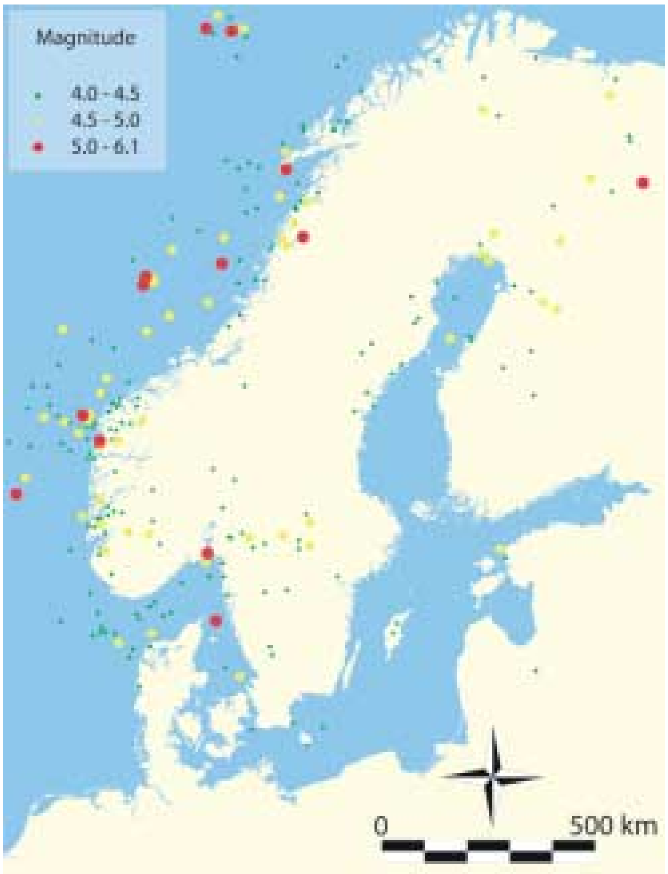


Figure 4-6. The figure shows earthquakes larger than M=4 in Scandinavia within the period 1375–1996. For the period before instruments were available, magnitudes were estimated from documented witnesses (Data from Fennoscandian Earthquake Catalogue, Dept seismology, Uppsala University).

4.8.3 What is the proper respect distance to faults?

In Japan, the Japan Society of Civil Engineers /JSCE, 2001/ recently presented a report on siting factors. Around 100 000 years is adopted as a premise of the time frame for geological predictions. Seismic impact on geological environment is not particularly considered in the screening of the Preliminary Investigation Areas by literature surveys. However it is proposed that "active faults" should be excluded to avoid the direct breakage of the disposal facility by faulting. In Japan, an active fault is defined as a fault that has shown repeated activity during the Quaternary times (~1,7 million years in the broad sense). In the JSCE report, an active fault is defined as fault that has shown repeated activity during the late Quaternary. As a rule of thumb a process zone is defined around the active faults as a "Concerning Factor". The width of the zone corresponds to about 1% of the fault length. This is in accordance with ideas proposed by e.g. /Vermilye and Scholz, 1998/. The /JSCE, 2001/ further suggested that mechanical and hydrological influences to the repository host rock within 2 km of an "active fault" should be investigated. If critical influences are found, the affected area should be excluded.

A similar approach is adopted by Department of Energy, USA, for the Yucca Mountain Project; the respect distance is fault specific and the facilities are engineered to withstand any hazardous effect of anticipated earthquakes /Stepp et al, 1995/.

Viewed in this context, the Swedish approach is similar to the ones adopted in Japan and USA. One difference is that all faults with significant regional extent are considered candidates for future reactivations. Accordingly, all faults surrounding any potential site for nuclear wastes must be examined and respect distances estimated for each fault.

SKB has not yet precisely defined how these site-and fault-specific "respect distances" will be estimated. Yet, this report, other material and the site-specific investigations will form a basis for a methodology to estimate appropriate respect distances. In the safety analyses SR 97, /SKB, 1999c/ the following generic values were used: The respect distances were set to 100 m on either side of the borders of regional deformation zones (> 10 km in length) and 50 m on either side of major local deformation zones (1–10 km in length). No respect distances were set for deformation zones smaller than 1 km in length. Regional deformation zones will not be permitted within the repository volume, but could bound the repository area or be crossed with the access ramp. Major local zones are permitted within the repository volume, but not permitted to intersect deposition tunnels. Minor local zones and larger fractures (> 100 m radii) are permitted to intersect deposition tunnels but not canister positions.

4.9 Advancements in methodology

It is becoming increasingly common to combine field records, as measured by seismic monitoring networks, with actual measurements of strain changes. The use of Global Positioning System to measure strain changes contribute to increased understanding of the relation between seismic and a-seismic deformation, the latter being displacements in faults that are not recorded as seismic signals, Figure 4-7.

SKB is currently installing seismic networks and small GPS-networks that are intended to provide additional insight into the site-specific behaviour at the potential repository sites in Sweden.

Dynamic effects of earthquakes on underground facilities are also studied by use of physical models of different kinds /Barton, 1986; Ghosh et al, 1996; Higuchi et al, 1999/ but numerical models are becoming more fashionable.

Dynamic modelling of earthquake effects on underground facilities has been performed by e.g. /Dowding, 1985; Dowding et al, 1983/. /Ma and Brady, 1999/ used the finite-difference code Distinct Element. /Tao and Zhang, 1998/ also used a version of the Distinct Element code. The work by /Hildyard et al, 2001/ using the WAVE-code (also developed by Dr P A Cundall) is interesting and also used by SKB /Christianson, 2001/. Several researchers have noted that ground motions in mining stopes are many times larger than in the solid rock /Hildyard et al, 2001/ and can be 4–10 times higher than a few metres into the rock when measured in boreholes. The advancement in modelling shows that apparent amplification of particle velocity is due to the excavation free surface and propagation of surface waves. The Rayleigh wave amplitude decays to 20% of its surface value within one wavelength of the surface. The amplification of motions at the surface is to 50% contributed to the free surface and 50% due to increased fracturing. The results are applicable to the mining-induced events where the events are close to the stopes and where the frequency spectrum still contains high frequencies.

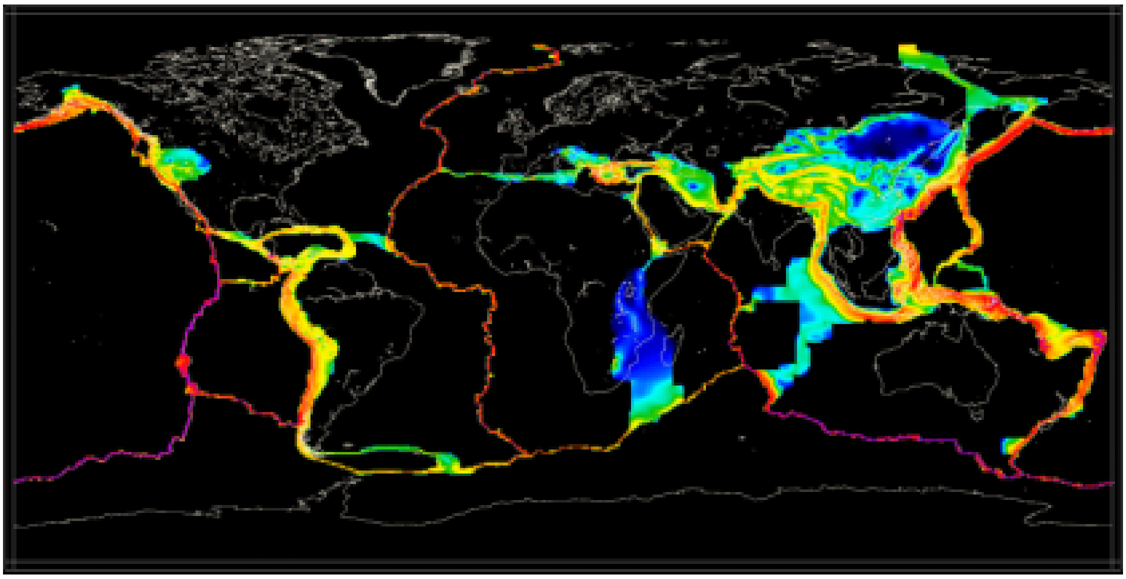


Figure 4-7. *Example Global Strain Rate Model: Contours of the second invariant of the model strain rate tensor field obtained by a least squares fit to a large set of world-wide geodetic velocities and fault slip rate in Asia. Where no fault slip rate data is used the style and direction (but not magnitude) of the model strain rate field were constrained, a priori, using the seismic moment tensors of all shallow events in the CMT catalogue /UNAVCO, 2001/.*

Recent work concerning dynamic earthquake effects on underground facilities is e.g. /Kurose, 2000/ where analytical models are developed as the basis for underground design-methods similar to the presently in use for surface facilities where there is

- a characteristic period of the underground facility,
- physical parameter that measures the vulnerability of the structure and
- a response spectrum suited to the stability analysis.

For the underground structures, the estimate of additional stresses induced by dynamic loading around the structure is important. The new method has successfully been applied to unlined tunnels, lined tunnels but also water-filled cavities (like boreholes) to reproduce water-level changes in boreholes due to earthquakes.

The model should also be able to analyse the behaviour of backfilled tunnels assuming that the backfill can be treated as an elastic inclusion.

For more in-depth research on the issue of “respect distance”, the methods and results reported by /Stein, 1999/ may be useful. The used models calculate stress and strain changes due to fault displacements, including co-seismic pore fluid changes, /Parsons et al, 1999; Toda and Stein, 2000/.

4.10 Information to the general public

Due to the very low seismic activity in Sweden at present, the Swedish population has virtually no practical experience of earthquakes. However, the possible effect of earthquakes on a repository is a Frequently Asked Question. Since the general public is concerned SKB consider it important to respect this concern and respond with readily accessible facts. The authors profited from the study-tour to also experience how earthquake information is shared with the general public. Based on this report and collected supporting information, SKB has the opportunity to prepare communication to the general public. The detailing of communication on earthquakes with the general public is however not within the scope of this project or report.

5 Conclusions

The main goal of this project was to evaluate the impact of earthquakes on the repository for spent nuclear fuel. An extensive literature survey, a study-tour with site visits and a substantial amount of interviews lead to the following conclusions:

Earthquake impact during the *pre-closure* phase:

- Damage due to shaking in an underground facility may occur if the peak ground acceleration exceeds 2 m/s^2. Sweden is located in the Baltic Shield that is seismically rather silent and will remain so in the foreseeable future. Seismic hazard has been calculated for Sweden and it is concluded that PGA greater than 2 m/s^2 is very unlikely the next coming 50-year period, in which the repository is planned to be constructed and operated.
- Damage due to shaking is very rare in underground facilities. Where such damage has occurred, the rock is either very poor or subject to very high stresses. None of these conditions will prevail in the Swedish repository. Most damage is also correlated to the presence of faults and the spent fuel will not be deposited in or close to important faults.
- Mining-induced earthquakes are known to cause damages in the mines. At the repository site it might be possible to experience local rock burst problems due to the heterogeneous rock strength and the varying rock stresses. It is expected that these events, in case they appear, will take place when the tunnels are excavated rather when the spent fuel is deposited.

Earthquake impact during the *post-closure* phase:

- The present seismic activity in Sweden is expected to increase considerably in connection to the retreat of ice sheets in future glaciations. Peak ground accelerations may exceed 2 m/s^2 in association with large earthquakes. However, the effects of shaking, such as fallouts, cracking of lining are reduced or eliminated since all tunnels will be backfilled by crushed rock and bentonite.
- The presence of the repository will not trigger earthquakes as the extraction ratio of the openings is very low compared to open stopes in a mine. There are also evidences for mines at great depth, that backfilling considerably lower the mining-induced seismic activity compared to the situation when tunnels are not backfilled.
- The buffer and canister shake as a solid body without producing excess shear stresses or liquefaction of the buffer. Water-level changes will occur due to earthquakes but most of the changes are temporary and water-levels will return to their original values within a few months. The density of the buffer around the canister is high enough to prevent liquefaction due to shaking.
- Brittle deformation of a rock mass will predominantly be located along reactivation of pre-existing fractures. The data emanating from faults intersecting tunnels show that creation of new fractures is confined to the immediate vicinity of the reactivated faults and that deformation in host rock is rapidly decreasing with the distance from the fault. By selection of appropriate respect distances the probability of canister damage due to faulting is further lowered.

- Data from deep South African mines show that rocks in a environment with non-existing faults and with low fracture densities and high stresses might generate faults in a previously unfractured rock mass. The Swedish repository will be located at intermediate depth, 400–700 m, where stresses are moderate and rock is moderatly fractured. The conditions to create these peculiar mining-induced features will not prevail in the repository environment. Should these faults anyhow be created, the canister is designed to withstand a shear deformation of at least 0.1 m. This corresponds to a magnitude 6 earthquake along the fault with a length of at least 1 km which is highly unlikely.
- Respect distance has to be site and fault specific. Field evidence gathered in this study indicates that respect distances may be considerably smaller (tens to hundres of m) than predicted by numerical modelling (thousands of m). However, the accumulated deformation during repeated, future seismic event has to be accounted for.

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Appendix A

A1.1 Damage scales

Although numerous intensity scales have been developed over the last several hundred years to evaluate the effects of earthquakes, the one currently most used in the Western world is the Modified Mercalli (MM) Intensity Scale. It was developed in 1931 by the American seismologists Harry Wood and Frank Neumann. The 12-grade scale I–XII is a mix of psychological, engineering and geological criteria to describe the effect of an earthquake. The Degree I am where earthquakes are not felt and the Degree XII where total destruction of surface facilities is implied. By polls and interviews the seismologist can arrive at a fair estimation of epicentre (the point on the earth's surface vertically above the point in the crust where a seismic rupture begins) and other properties of the earthquake.

China and Japan have their own scale, the People's of Republic China Intensity Scale and the Japan Meteorological Agency Scale (JMA). The Figure A-1 is a comparison of different damage scales in use. The detailed descriptions of the Modified-Mercalli Scale and the new JMA-scale in force since April 1, 1996 are attached in the Table A-1 and Table A-2 respectively.

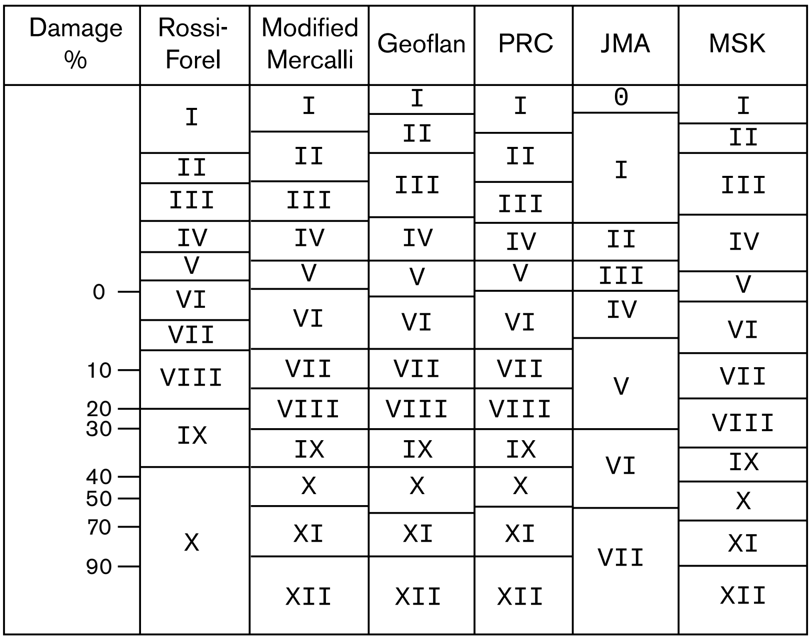

Figure A-1. *Comparison of different damage scales /After Blong, 1998/.*

Table A-1. Description of the Modified Mercalli Scale.

MM-Intensity	Description of Shaking Severity	Summary Damage Description	Full Description
I	–	–	Not felt. Marginal and long period effects of large earthquakes.
II	–	–	Felt by persons at rest, on upper floors, or favourably placed.
III	–	–	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV	–	–	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.
V	Light	Pictures Move	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI	Moderate	Objects Fall	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).
VII	Strong	Nonstructural Damage	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
VIII	Very Strong	Moderate Damage	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX	Violent	Heavy Damage	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas sand and mud ejected, earthquake fountains, sand craters.

MM-Intensity	Description of Shaking Severity	Summary Damage Description	Full Description
X	Very Violent	Extreme Damage	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI	–	–	Rails bent greatly. Underground pipelines completely out of service.
XII	–	–	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Explanation of masonry

A	Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.
B	Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.
C	Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.
D	Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Table A-2. The Japan Meteorological Agency (JMA) Intensity Scale and Seismic Intensity (New measure after April 1, 1996, based on three components ground acceleration).

Seismic Intensity	JMA Scale	People	Indoor situations	Outdoor situations	Wooden houses	Reinforced-concrete buildings	Lifelines	Ground and slopes
−0.5	0	Imperceptible to people.						
0.5–1.5	1	Felt by only some people in the building.						
1.5–2.5	2	Felt by many people in the building. Some sleeping people awake.	Hanging objects such as lamps swing slightly.					
2.5–3.5	3	Felt by most people in the building. Some people are frightened.	Dishes in a cupboard rattle occasionally.	Electric wires swing slightly.				
3.5–4.5	4	Many people are frightened. Some people try to escape from danger. Most sleeping people awake.	Hanging objects swing considerably and dishes in a cupboard rattle. Unstable ornaments fall occasionally.	Electric wires swing considerably. People walking on a street and some people driving automobiles notice the tremor.				
4.5–5.0	5Lower	Most people try to escape from a danger. Some people find it difficult to move.	Hanging objects swing violently. Most unstable ornaments fall. Occasionally, dishes in a cupboard and books on a bookshelf fall and furniture moves.	People notice electric-light poles swing. Occasionally, windowpanes are broken and fall, concrete-block walls without reinforced wire collapse, and roads suffer damage.	Occasionally, less earthquake-resistant houses suffer damage to walls and pillars.	Occasionally, cracks are formed in walls of less earthquake-resistant buildings.	A safety device cuts off the gas service at some houses. On rare occasions water pipes are damaged and water service is interrupted. [Electrical service is interrupted at some houses.]	Occasionally, cracks appear in soft ground, and rockfalls and small slope failures take place in mountainous districts.

Seismic Intensity	JMA Scale	People	Indoor situations	Outdoor situations	Wooden houses	Reinforced-concrete buildings	Lifelines	Ground and slopes
5.0–5.5	5Upper	Most people try to escape from a danger. Some people find it difficult to move.	Most dishes in a cupboard and most books on a bookshelf fall. Occasionally, a TV set on a rack falls, heavy furniture such as a chest of drawers falls, sliding doors slip out of their groove and the deformation of a doorframe makes it impossible to open the door.	In many cases, concrete-block walls without reinforced wire collapse and tombstones overturn. Many automobiles stop because it becomes difficult to drive. Occasionally, poorly installed vending machines fall.	Occasionally, less earthquake-resistant houses suffer heavy damage to walls and pillars and lean.	Occasionally, large cracks are formed in walls, crossbeams and pillars of less earthquake-resistant buildings and even highly earthquake-resistant buildings have cracks in walls.	Occasionally, gas pipes and/or water mains are damaged. [Occasionally, gas service and/or water service are interrupted in some regions.]	
5.5–6.0	6Lower	Difficult to keep standing.	A lot of heavy and unfixed furniture moves and falls. It is impossible to open the door in many cases.	In some buildings, wall tiles and windowpanes are damaged and fall.	Occasionally, less earthquake-resistant houses collapse and even walls and pillars of highly earthquake-resistant houses are damaged.	Occasionally, walls and pillars of less earthquake-resistant buildings are destroyed and even highly earthquake-resistant buildings have large cracks in walls, crossbeams and pillars.	Gas pipes and/or water mains are damaged. [In some regions, gas service and water service are interrupted and electrical service is interrupted occasionally.]	Occasionally, cracks appear in the ground, and landslides take place.

Seismic Intensity	JMA Scale	People	Indoor situations	Outdoor situations	Wooden houses	Reinforced-concrete buildings	Lifelines	Ground and slopes
6.0–6.5	6Upper	Impossible to keep standing and to move without crawling.	Most heavy and unfixed furniture moves and falls. Occasionally, sliding doors are thrown from their groove.	In many buildings, wall tiles and windowpanes are damaged and fall. Most concrete-block walls without reinforced wire collapse.	Many less earthquake-resistant houses collapse. In some cases, even walls and pillars of highly earthquake-resistant houses are heavily damaged.	Occasionally, less earthquake-resistant buildings collapse. In some cases, even highly earthquake-resistant buildings suffer damage to walls and pillars.	Occasionally, gas mains and/or water mains are damaged. [Electrical service is interrupted in some regions. Occasionally, gas service and/or water service are interrupted over a large area.]	
6.5–	7	Thrown by the shaking and impossible to move at will.	Most furniture moves to a large extent and some jumps up.	In most buildings, wall tiles and windowpanes are damaged and fall. In some cases, reinforced concrete-block walls collapse.	Occasionally, even highly earthquake-resistant houses are severely damaged and lean.	Occasionally, even highly earthquake-resistant buildings are severely damaged and lean.	[Electrical service, gas service and water service are interrupted over a large area.]	The ground is considerably distorted by large cracks and fissures, and slope failures and landslides take place, which occasionally change topographic features.

A1.2 Definitions of magnitudes

/Richter, 1958/ devised a method where the earthquake is assigned a magnitude based on local measurements by instruments. The magnitude M of the earthquake is related to the energy release E by:

$$\log(\mathbf{E}) = 1.5 \cdot \mathbf{M} + 11.4 \qquad \text{A-1}$$

where

E = energy (in ergs, 10^7 ergs ~1 J)

M = the magnitude of the earthquake.

Richter originally defined M as:

$$\mathbf{M} = \log\left(\frac{\mathbf{A}}{\mathbf{A}_0}\right) \qquad \text{A-2}$$

where **A** is the maximum amplitude recorded at the Wood-Anderson seismograph at a distance of 100 km from the epicentre and $\mathbf{A_0}$ is an amplitude equal to 1 µm.

The MM-scale and the M-scale has with good results been related in North-America by e.g. /Lomnitz, 1974/:

$$\mathbf{I} = 8.16 + 1.45 \cdot \mathbf{M} - 2.46 \cdot \log(\mathbf{R}) \qquad \text{A-3}$$

where

M = Magnitude by the Richter-scale

I = Intensity (MM-scale); and

R = Focal distance (in km) and > 100 km (The focal distance is the distance from the seismometer to the point within the earth where an earthquake rupture starts.)

There are presently several types of magnitude scales in use, see Table A-3.

Table A-3. Definitions of magnitudes /After Ates et al, 1995/.

Magnitude	Definition	Application
Local, M_L	^{10}log of peak amplitude (in microns) measured on Wood-Anderson seismographs at a distance of 100 km from source and on firm ground. In practice, corrections are made to account for different instrument types, distances and site conditions.	Used to represent sizes of moderate earthquakes. More closely related to damaging ground motion than other magnitude scales.
Surface wave M_S	^{10}log of maximum amplitude of surface waves with 20 s period.	Used to represent sizes of large earthquakes.
Body wave M_B	^{10}log of maximum amplitude of P-waves within 1 s period.	Useful for assessing sizes of large, deep-focus earthquakes, which do not generate strong surface waves.
Moment M_W	Based on total elastic strain energy released by fault rupture, which is related to seismic moment M_O (M_O=G·A·D, where G=modulus of rigidity, A=area of fault rupture surface and D=average fault displacement).	Avoids the difficulty associated with inability to distinguish between two very large events of different fault lengths.

A1.3 Attenuation of seismic waves

The magnitude of seismic waves is governed by the magnitude and distance to the earthquake. Several empirical relations are suggested for the attenuation as related to magnitude and distance and they are different for different geological environments. For Scandinavian hard rock conditions, /Wahlström and Grünthal, 2000b/ suggest:

$$\ln(\mathbf{PGA}) = -2.143 + 0.751 \cdot \mathbf{M}_w - 1.04 \cdot 10^{-3} \cdot \mathbf{R} - 0.815 \cdot \ln(\mathbf{R}) \qquad \text{A-4}$$

where **PGA** is horizontal Peak Ground Acceleration (m/s^2), M_W, the moment magnitude and R hypocentral distance (km). The M_w=1.2 + 0.28 M_L(UPP) + 0.06[M_L(UPP)]^2, where UPP is the seismometer in Uppsala, Sweden.

In Japan, however, the attenuation is described by /Fukushima and Tanaka, 1990/.

$$\log(\mathbf{PGA}) = 0.41 \cdot \mathbf{M} - \log\left(\mathbf{R} + 0.032 \cdot 10^{0.41 \cdot \mathbf{M}}\right) - 0.0034 \cdot \mathbf{R} + 1.30 \qquad \text{A-5}$$

where **PGA** is the peak ground acceleration (cm/s^2) from two horizontal components at each site, **M** the surface-wave magnitude and **R** the shortest distance between the site and the fault rupture (km).

The attenuation is also dependent on the frequency of the wave at its source. High frequency and high acceleration waves attenuate very rapidly near the seismic focus. The frequency content is important when considering underground facilities. Frequencies causing damage at the surface is in the range of 1–10 Hz but should be much higher when considering shaking effects on underground openings. Suppose the celerity of the shear wave is around 2500 m/s and the typical span of the tunnel is 8 m /Dowding, 1979/. The resulting motions in the rock mass would be out of phase over distances equal to ¼ the wavelength. Since the largest block that can move into an excavation will have a maximum dimension equal to the span D of the opening, the lowest frequency that would produce the differential acceleration will be $f=C_S/4D$ ~100 Hz. Such frequencies are only possible for close-by earthquakes or events due to development blasting. The shaking effect for an underground facility thus may be more influenced by a small earthquake nearby having a high-frequency content than a larger far away where the high frequencies attenuate. An expression for attenuation of seismic waves accounting for the frequency content is found in /Jaeger and Cook, 1979/.

$$A = \frac{A'}{r} \cdot e^{-\alpha(r-1)} \qquad \text{A-6}$$

where

A = the amplitude at the distance r from the source

A'= the amplitude at unit distance from the source.

$$\alpha = \frac{\pi \cdot f}{Q \cdot c} \qquad \text{A-7}$$

where

f = frequency of the wave

c = the velocity of propagation.

$$Q = \frac{2\pi W}{\Delta W} \qquad \text{A-8}$$

where

ΔW = amount of energy lost in taking a body through a stress cycle and
W = the elastic strain energy in the body at the maximum stress during that cycle.

Typical Q-value for granite is 40–70 and typical c_S-values around 3500 m/s.

One of the reasons there is less damage to underground facilities is also the relative absence of surface waves. The wave velocity c of the surface waves is in the order of 3000 m/s and damaging frequencies f are in the order of 100 Hz. The depth influence is half the wavelength:

$$\lambda = \frac{\mathrm{c}}{2\,\mathrm{f}} = 15\mathrm{m} \qquad \text{A-9}$$

For the low frequencies, 1 Hz, the influence then is down to 1.5 km.

Comparison of maximum acceleration due to earthquakes generally shows that the acceleration decays with depth. Examples are found in measurements in the Kamaishi mine in Japan, where records deeper than 150 m has a tendency to decrease to ¼ to ½ of that at the ground surface /Ishimaru and Shimizu, 1997/.

/McGarr et al, 1981/ developed an attenuation formula to be applied in solid rock for near-field earthquakes, based on South-African experience with mining-induced earthquakes. The peak particle velocity PPV is expressed as:

$$\log(\mathbf{PPV}) = 3.95 + 0.57 \cdot \mathbf{M} - \log(\mathbf{R}) \qquad \text{A-10}$$

where **PPV** is in cm/s, **R** in cm and **M** is the magnitude.

Recent studies by /Cichowicz, 2001/ describe a semi-empirical model to estimate PPV at a distance. The model is based on South-African mining-induced events of magnitude 1.2–2.4 produced at a distance of 80–140 m. The Peak Ground Velocity (PGV) was in the range of 0.30–0.46 m/s and frequency in the range of 10–30 Hz. The attenuation for far field data is expressed as:

$$\mathbf{V(R)} = \frac{\mathbf{c \cdot M_o}}{\mathbf{R^{1.5}}} \cdot \mathbf{exp(-\pi \cdot f_o \cdot R / V_s \cdot Q)} \qquad \text{A-11}$$

where **V** is Peak Particle Velocity as a function of the distance **R**, **c** a constant $5 \cdot 10^{-9}$, $\mathbf{M_o}$ is the seismic moment, $\mathbf{f_0}$ the dominant frequency in the signal, **Q** is the quality factor (=200) and $\mathbf{V_s}$ the velocity is the shear-wave (3600 m/s) for the site data studied.

A1.4 Why is there less damage underground that at surface?

Underground facilities experience much less damage than at the surface /Ates et al, 1995/ as:

- Underground structures are strongly coupled to the rock so there is less potential for the structures to attain its resonance frequency.
- The secondary surface waves, which are the main cause of damage at the surface, are nearly absent underground; and
- The rock mass is generally stronger at depth compared to the near surface strata which supports building foundations.

Ground acceleration attenuates with distance and the frequency content change. It is also well-known that the actual ground motion attenuates with depth. Measurements were performed at the Kamaishi Mine /Ishimaru and Shimizu, 1997/ from February 1990 to December 1995. 249 earthquakes at a distance from 20 km to 250 km were simultaneously recorded at surface and at levels 140 m, 315 m and 615 m below the surface. The maximum magnitude recorded was an 8.1 magnitude earthquake at an epicentral distance about 675 km. The maximum accelerations at the 615 m lever were about ½ to ¼ of the acceleration at the surface, which is in line with previous observations by /Komada et al, 1981/. It should be noted that the attenuation is very dependent on the conditions at the surface. /Pratt et al, 1980/ refers to attenuation up to 6 where the surface seismometers are located in alluvial material.

The damage at the surface is very much associated with the generated surface waves (Love- and Rayleigh waves). The amplitudes of waves travelling within low-velocity layers can be predicted from physical principles. The low-velocity layers consist of damaged or fissured rock close to surface or unconsolidated sediments. When a seismic wave encounters such a low-velocity, near-surface low-velocity layer, three things occur (Figure A-2):

- the amplitude of the wave increases,
- the wave path is bent upwards, and
- the wave becomes trapped in the near-surface layer.

The first behaviour can be understood with respect to energy balance. The energy associated to a wave of given amplitude is lower in a low-velocity medium than in a high-velocity medium. However, wave energy is conserved when waves move from one medium to another so the amplitude of a wave will increase when the medium velocity decreases; when a wave slows down, its amplitude grows.

Seismic waves are just physical waves following ordinary physical principles so the second behaviour is nothing else than the principle of refraction (Snell's law) in optics.

The third principle is what concerns us here. The trapped wave behaves as a surface wave, giving rise to an exponentially decaying motion in the vertical direction in the high-velocity layer. In the horizontal direction, the trapped surface wave in the low-velocity layer attenuate as $r^{-0.5}$, while the body waves travelling directly from the hypocentre to the tunnel attenuates faster, in the range r^{-1} to r^{-2}, assuming a linear elastic model.

The motion at the surface of the low-velocity layer, where buildings are located, thus is much higher than inside the high-velocity layer, where tunnels and other underground facilities are located.

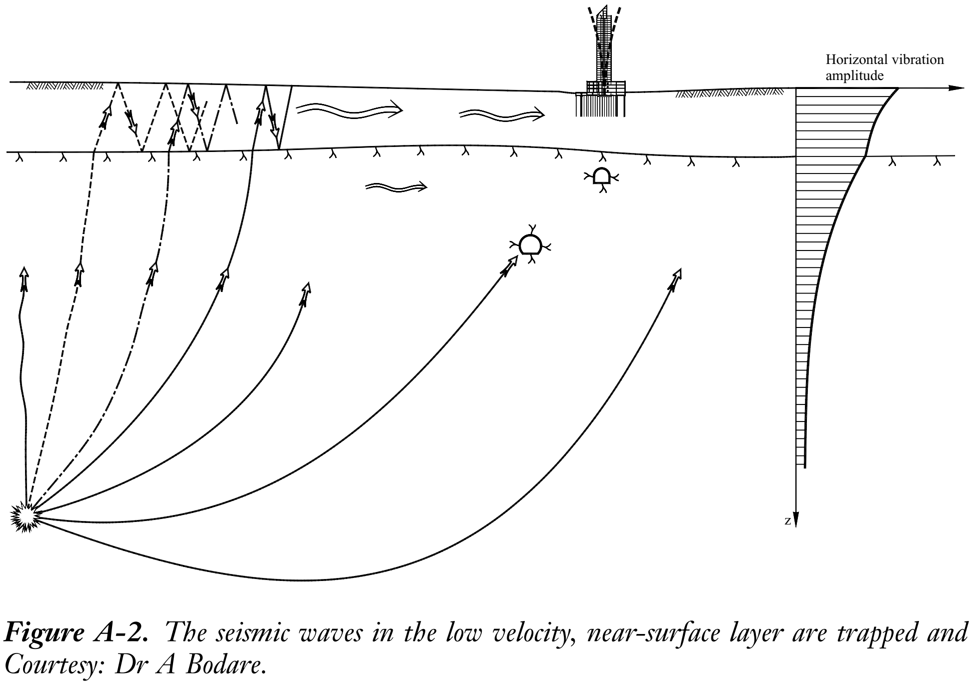

Figure A-2. *The seismic waves in the low velocity, near-surface layer are trapped and amplified. Courtesy: Dr A Bodare.*

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