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Authors: Goodluck I. Ofoegbu
Kevin J. Smart

Technical Note

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Shear movement of near-field rock due to large earthquakes

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Uppdraget är en del av granskningen som rör den långsiktiga utvecklingen av bergmassan omgivande det tilltänkta slutförvaret. Detta uppdrag fokuserar på att studera SKB:s hantering av jordbävningars påverkan på sprickor i slutförvarets närområde. Frågor som berörs är uppkomst av skjuvrörelser och deras påverkan på slutförvaret, tillväxt av sprickor samt uppkomst av nya sprickor. Uppdraget går även ut på att titta på tillförlitligheten på utförda analyser.

Författarnas sammanfattning

Denna rapport är en del av granskningen som externa experter utfört för Strålsäkerhetsmyndighetens (SSM) räkning i den inledande granskningsfasen. Målet med den inledande granskningsfasen är att få en bred bild av informationen i SR-Site och dess referenser, och då särskilt för att identifiera områden där kompletteringar eller förtydliganden behövs från Svensk Kärnbränslehantering AB (SKB). Personalen på Southwest Research Institute (SwRI) – Center for Nuclear Waste Regulatory Analyses (CNWRA) har granskat den numeriska modellering som SKB utfört för att kvantifiera potentiell rörelse i sprickor på grund av jordbävning. SKB har bestämt att kapselskador uppkomna på grund av jordbävning behöver omhändertas i säkerhetsanalysen för ett slutförvar av KBS-3-typ. Detta eftersom jordbävningsinducerad skjuvning av intilliggande berg kan medföra rörelser i befintliga sprickor som kan generera påkänningar tillräckliga för att påverka kapselns mekaniska integritet.

I säkerhetsanalysen SR-Site slår SKB fast att en rörelse på 0,05 m i en spricka som korsar deponeringshålet medför skada på kapseln. SKB har använt sig av numerisk modellering för att definiera potentiell magnitud för rörelser i sprickor som en funktion av avståndet till den jordbävningsbärande förkastningen och storleken på befintliga sprickor. Baserat på denna modell har SKB definierat en kritisk sprickstorlek för varje punkt i bergmassan som en funktion av avståndet till kända förkastningar. SKB har föreslagit att deponeringshål vars föreslagna lokalisering korsas av sprickor större än den kritiska storleken undviks, eller att sannolikheten för kapselskador där deponeringshål oavsiktligt korsas av sådana sprickor utvärderas.

SKB har i sina analyser använt sig av en geologisk modell där en jordbävningsbärande förkastning korsar en generisk bergmassa, här representerad av en uppsprucken bergmassa. Modellen utsattes för mekaniska förhållan-

den för att simulera jordbävningar på grund av post-glaciala förkastningar i svensk berggrund. SKB använde sig av en serie av dynamiska mekaniska förhållanden i modellen för att beräkna seismiskt uppkommen rörelse i existerande sprickor i den generiska bergmassan. Personalen på SwRI-CNWRA kom fram till att SKB:s analys är ändamålsenlig för att bedöma jordbävningsinducerade skjuvdeformationer eftersom (i) analysen utfördes med hjälp av en väletablerad datakod (3DEC) för modellering av mekaniska förändringar i en sprickig bergmassa; (ii) en meningsfull spridning på parametervärden användes i modelleringen, som till exempel geometrin på förkastningar och sprickor, mekaniska egenskaper samt magnitud och riktning på in-situ-spänningar; och (iii) tillvägagångssättet för att initiera och propagera förkastningsrörelse var konsistent med de förmodade mekaniska förändringar som förknippas med dynamisk förkastningsrörelse. Trots detta har personalen på SwRI-CNWRA identifierat fyra osäkerheter i SKB:s modellering som kan påverka den beräknade storleken på sprickrörelserna samt SKB:s tillvägagångssätt för att kontrollera potentialen för skadlig jordbävningsinducerad skjuvdeformation av omgivande berg. Först och främst, har SKB inte visat att markrörelser uppkomna vid jordbävningssimuleringar väl motsvarar en för platsen för slutförvaret karaktäristisk seismisk händelse.

Eftersom de mekaniska effekterna av en jordbävning kontrolleras av storlek och frekvens på markrörelsen (acceleration, hastighet och förskjutning), utvärderas vanligen effekten av en jordbävning på en konstruktion eller ett geologiskt medium mot markrörelser som anses representativa för jordbävningen. SKB valde för modellen parametrar som till exempel momentmagnitud, spänningslättnad och hastighet för förkastningsrörelse för att kontrollera egenskaper hos den simulerade jordbävningen. Trots detta gjorde SKB ingen systematisk analys av simulerade markrörelser för att visa hur valda parametrar faktiskt är relaterade till markrörelser representativa för den tilltänkta platsen för slutförvaret i Forsmark. För det andra, tog SKB inte hänsyn till potentiell sammanslagning av sprickor under en seismisk händelse och räknade därmed inte in några effekter från sammanslagning eller tillväxt av sprickor vid beräkning av storlek på skjuvrörelse som en funktion av sprickstorlek.

För det tredje, har SKB inte givit en tillräcklig beskrivning av den rumsliga och tidsmässiga utvecklingen för bergsspänningarna för att kunna utvärdera beräknade skjuvrörelsemönster och hur de relaterar till geologiska, mekaniska och påtvingade skjuvningsförhållanden för en jordbävningsalstrande förkastning. För det fjärde, tar SKB:s analyser inte hänsyn till seismiska händelser uppkomna på grund av rörelser i en förkastning som inte ger utslag på markytan och som kan bete sig annorlunda än de modellerade händelserna. Deformationsgradienter och utvecklingen av spänningsfältet i uppsprucken bergmassa som ligger ovanpå en glidande oupptäckt förkastning kan särskilja sig betydligt från de simulerade förhållandena för bergmassan i modellen. I en sådan händelse kan effekterna av en oupptäckt förkastning leda till behov av en reviderad beräkning av den potentiella uppkomna rörelsen som en funktion av avstånd till jordbävningsbärande förkastning.

Baserat på denna granskning rekommenderar personalen på SwRI-CNWRA att SSM begär kompletterande information från SKB för att kunna ta övergripande hänsyn till dessa potentiella angelägenheter gällande säkerheten. Personalen på SwRI-CNWRA rekommenderar också att SSM utför oberoende analyser för att utvärdera (i) potential för brott av bergbrygga (d.v.s. relativt intakt berg mellan intilliggande sprickor) under en seismisk händelse, och (ii) effekten på sprickstabiliteten av rörelser i en oupptäckt förkastning och rörelsestorleken i ovanliggande bergmassa.

Projektinformation

Kontaktperson på SSM: Lena Sonnerfelt
Diarienummer ramavtal: SSM2011-3639
Diarienummer avrop: SSM2012-109
Aktivitetsnummer: 3030007-4023

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

This assignment is part of the review regarding the long-term evolution of the rock surrounding the repository. This assignment focuses on the handling by SKB on the impact of earthquakes on repository structures. Issues regarded are shear movements and their impact on the repository, growth of fractures and the initiation of fractures. The assignment includes assessment of the robustness of the analyses performed.

Summary by the authors

This technical note is part of a set of reviews for Swedish Radiation Safety Authority (SSM) by external experts to assist with the Initial Review Phase. The overall goal of the Initial Review Phase is for SSM to achieve a broad coverage of the information provided in SR-Site and its supporting references and in particular to identify where complementary information or clarifications need to be delivered by Swedish Nuclear Fuel and Waste Management Company (SKB). Southwest Research Institute® (SwRI®)–Center for Nuclear Waste Regulatory Analyses (CNWRA®) staff have reviewed the numerical modelling that SKB performed to quantify potential slip on existing fractures due to an earthquake.

SKB has determined that canister damage due to an earthquake needs to be considered in the safety assessment of the KBS–3 disposal design because shear deformation of the near field rock due to seismically induced slip on existing fractures could generate forces sufficient to challenge the mechanical integrity of the waste canister. For the SR Site safety assessment, SKB considers that a fracture slip of 0.05 m across a deposition hole corresponds to canister damage. SKB used numerical modelling to define the potential magnitude of induced fracture slip as a function of the distance from an earthquake-generating fault and the size of existing fractures. Based on the model, SKB defined a critical fracture size for each location as a function of distance from known faults. SKB proposed to avoid deposition hole locations that were intersected by fractures greater than the critical size or to assess the probability of canister damage for deposition holes that may inadvertently intersect such fractures.

SKB performed analyses using a geologic model of an earthquake-generating fault that intersects a fractured rock body representing a generic host rock. The model was subjected to mechanical conditions to simulate earthquakes due to post-glacial faulting in the Swedish bedrock. SKB

applied a series of dynamic mechanical conditions in the model to assess seismically induced slip on existing fractures in the generic host rock. The SwRI–CNWRA staff concluded that the SKB analysis is appropriate to assess induced shear deformation due to earthquakes because (i) the analysis was performed using a well-established computer code (3DEC) for modelling mechanical changes in a fractured rock mass; (ii) the modelling investigated a meaningful range of parameter values, such as fault and fracture geometry, mechanical properties, and in situ stress magnitude and orientation; and (iii) the procedures used to initiate and propagate fault rupture were consistent with the anticipated mechanical changes associated with dynamic fault slip. Nevertheless, the SwRI–CNWRA staff identified four uncertainties in the SKB modelling that could affect SKB's calculated fracture slip magnitudes and the implementation of the SKB approach to controlling the potential for damaging shear deformation of the near-field rock due to seismic events.

First, SKB has not demonstrated that ground motions due to the simulated earthquakes adequately represent the characterized seismic events for the target repository site. Because the mechanical effects of an earthquake are controlled by the ground motion (acceleration, velocity, or displacement) magnitude and frequency, the effect of an earthquake on a constructed structure or geologic medium is typically assessed against the ground motions that are considered to be representative of the earthquake. SKB selected model parameters such as moment magnitude, stress drop, and fault slip velocity to control the characteristics of the simulated earthquake. However, SKB did not provide a systematic analysis of the simulated ground motions to show how the selected parameters actually relate to the representative ground motions for a target repository site at Forsmark. Second, SKB did not consider the potential coalescence of fractures during a seismic event and, therefore, did not account for any effects of fracture coalescence and growth on the calculated magnitude of slip versus the fracture size.

Third, SKB did not provide adequate description of the spatial and temporal stress evolution to permit an evaluation of the calculated slip patterns and their relationships with the geological, mechanical, and imposed-slip conditions on the source fault. Fourth, the SKB analysis did not consider seismic events due to slip on a blind fault, which would differ from the modelled events. The deformation gradients and stress state evolution in a fractured rock medium that overlies a slipping blind fault could be significantly different from the simulated conditions in the target host rock region of the SKB model. In such an event, effects of a blind fault could lead to revised estimates of potential induced slip as a function of distance from a potential earthquake-source fault.

Based on the review, the SwRI–CNWRA staff recommend that SSM request the SKB to provide supplementary information to allow a more complete consideration of these potential safety concerns. The SwRI–CNWRA staff also recommend that SSM perform independent analyses to examine (i) the potential failure of a rock bridge (i.e., relatively intact rock separating adjacent rock fractures) during a seismic event and (ii) the effects of a slipping blind fault on fracture stability and on slip magnitudes in an overlying fractured rock.

Project information

Contact person at SSM: Lena Sonnerfelt

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myndigheten
Swedish Radiation Safety Authority

Authors: Goodluck I. Ofoegbu, Kevin J. Smart
Southwest Research Institute, Texas, USA

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Contents

1. Introduction

On 16 March 2011, the Swedish Radiation Safety Authority (SSM) received a license application from the Swedish Nuclear Fuel and Waste Management Company (SKB) for construction of a spent nuclear fuel repository to be located in Forsmark, Östhammar Municipality as well as to build an encapsulation facility for spent nuclear fuel in Oskarshamn. The safety assessment SR-Site, which was part of the submitted license application materials, is being reviewed by SSM in a stepwise and iterative fashion. The first step is called the Initial Review Phase. The overall goal of the Initial Review Phase is for SSM to achieve a broad coverage of the information provided in SR-Site and its supporting references and in particular to identify where complementary information or clarifications need to be delivered by SKB.

In TR–10–48 (SKB, 2010), the SKB geosphere process report for the safety assessment SR-Site SKB identified that the shear deformation of the near-field rock due to seismically induced slip on fractures, a potential effect of earthquakes, was relevant to the safety assessment of the KBS–3 disposal design. In TR–08–11 (Fälth et al., 2010), which discussed the effects of large earthquakes on a KBS–3 repository, SKB stated that seismically induced slip on fractures that intersect deposition holes could impair the integrity of the buffer-canister system if the slip magnitude and velocity are large enough to generate forces sufficient to cause plastic deformation and potential damage of the canister. For the SR-Site safety assessment, SKB considered a fracture slip of 0.05 m across a deposition hole as indicating canister damage, irrespective of the slip velocity and intersection geometry between the fracture and deposition hole. Accordingly, Southwest Research Institute® (SwRI®)–Center for Nuclear Waste Regulatory Analyses (CNWRA®) staff reviewed the numerical modelling that SKB performed to quantify the amount of potential slip on existing fractures due to an earthquake.

The review consisted of an evaluation of SKB information in TR–08–11 (Fälth et al., 2010) and other relevant information from literature (e.g., Stein and Yates, 1989; Hauksson et al., 1995; Shen et al., 1995; Trifu and Urbancic, 1996; Bobet and Einstein, 1998; Talebian et al., 2004; Lee and Jeon, 2011). The SKB information is presented clearly and was developed based on numerical model analyses performed using a well-established geomechanics modelling code (3DEC) and appropriate ranges of mechanical and geometrical properties of the rock mass. Also, SKB used well-established procedures to model faulting processes and effects. Therefore, the SKB calculated results and insight regarding faulting effects on fractures can be used to support an assessment of seismically induced shear deformation around deposition holes. However, the review identified potential sources of uncertainty that need to be evaluated further to support using the SKB approach.

2. Description of SKB analysis

To assess seismically induced fracture slip in a repository host rock in Chapter 4 of TR–08–11 (Fälth et al., 2010), SKB performed analyses using a model of an earthquake-generating fault that cuts through a zone of fractured rock and "daylights" (i.e., intersects) at the ground surface. The fractured rock zone is represented in the model as a rectangular slab (referred to as the *target fracture region* in the model) with mid-depth at 500 m below the ground surface. The horizontal and vertical dimensions of the slab are large enough to completely contain several variously oriented circular planes of 150 m radius. The circular planes represent fractures in the host rock of a hypothetical disposal design. SKB used the model to assess induced slip on the fractures (referred to as *target fractures* in the model) due to dynamic ground motion generated by slip on the simulated earthquake fault. The earthquake-generating fault (also referred to as the *primary fault* in the model) consists of a rectangular surface that intersects the target fracture region and extends several kilometers vertically and laterally. As SKB described in Chapter 4 of TR–08–11 (Fälth et al., 2010), the target fracture region and the primary fault are embedded in a three-dimensional model domain that is extended to permit the application of static and dynamic boundary conditions appropriate for simulating slip events on the primary fault.

SKB used the model to assess the effects of earthquakes due to reverse slip (i.e., hanging wall moves up relative to footwall) on a steeply or shallowly dipping fault, which, according to SKB, are typical of earthquakes due to post-glacial faulting in the Swedish bedrock. For the assessment, SKB performed a series of dynamic analyses to simulate such earthquakes and to calculate any resulting slip on the target fractures. In the analysis, an earthquake was simulated by initiating slip rupture at a predetermined point on the primary fault and then propagating the rupture at a predetermined rate through the fault surface. Slip rupture was simulated by reducing the shear strength of the primary fault to zero or to a small residual value from an initial value that was sufficient to prevent slip under initial loading conditions. The simulated rupture caused stress waves and displacements (ground motion) to propagate through the model domain and caused the target fractures to slip by different magnitudes and rates. The modelled fault geometry and initial rock stress were controlled to vary the moment magnitude and the stress drop of the simulated earthquake. Also, the dip magnitude and dip direction of the target fractures were varied as SKB described in Tables 4-2 and 4-4 of TR–08–11 (Fälth et al., 2010), which affected the initial stability margin of the target fractures and their potential to slip during a seismic event. The model combinations that were derived from varying the characteristics of the simulated fault and target fractures resulted in a range of seismically induced slip magnitudes and velocities on the target fractures.

SKB drew the following conclusions from the modelling results.

1. The simulated seismic events caused slip on variously oriented fractures at various distances in the hanging wall and footwall sides of the fault.

2. Fractures close to the fault developed an unstable stress condition (i.e., a shear stress greater than the shear strength of the fracture surface) that persisted after the end of the simulated seismic event.

3. An unstable stress condition for fractures occurred on three planes in the footwall of the fault for a short period during the seismic event, but the stress condition changed to stable at the end of the period and remained

stable thereafter. The unstable state occurred because of dynamic stress oscillations during the seismic event.

4. The stress conditions with respect to slip stability on planes at the same distance from the fault in the hanging wall and footwall evolved differently during the seismic event. The calculated results show a plane in the footwall that attained an unstable stress condition during the event. A similarly oriented plane in the hanging wall at the same distance from the fault did not attain any unstable condition.

5. The magnitude of seismically induced slip on existing fractures is strongly dependent on distance from the source fault. The calculated results indicate that both the peak slip magnitude for the entire target fracture population and the maximum slip magnitude for a given fraction of the target fractures decrease as distance from the fault increases.

6. The velocity of seismically induced slip on existing fractures also appears strongly dependent on distance from the earthquake source fault. Slip velocity decreases as distance from the fault increases.

7. Slip velocity correlates linearly with slip magnitude (i.e., a greater slip magnitude implies a greater slip velocity).

8. Slip magnitude correlates linearly with fracture size. Therefore, the calculated slip for model fractures of 150 m radius can be scaled linearly to determine the magnitude of seismically induced slip on existing fractures of arbitrary size.

In Chapter 7 of TR–08–11 (Fälth et al., 2010), SKB used the information described in items (5)–(8) to calculate ranges of stand-off (or respect) distance from existing faults for deposition holes and for the critical fracture radius (i.e., minimum radius of a fracture that could slip 0.05 m or more during a seismic event) within a given range of stand-off distance in Figure 7-3 of TR–08–11 (Fälth et al., 2010). SKB developed a set of stand-off distances and critical fracture radii for faults with a surface trace length of 3–5 km and a different set for faults with surface trace length greater than 5 km. SKB stated that deposition holes intersected by fractures with radii greater than the critical radius for the stand-off distance range would not be included in a disposal design layout. Also, SKB provided a relationship for estimating the probability of canister damage for deposition holes intersected by undetected fractures greater than the critical radius for the location of the deposition hole.

3. Evaluation of SKB analysis

SKB has proposed to use sets of stand-off distance ranges, and a critical fracture radius for each range, to limit the potential for damaging fracture slip occurring during a seismic event. The approach was developed based on numerical model analyses performed using a well-established geomechanics modelling code (3DEC). SKB considered appropriate ranges of fault and target fracture geometries, mechanical properties, and *in situ* stress magnitudes and orientations. The approaches used to initiate and propagate slip rupture on the source fault and calculate target fracture response are based on well-established procedures. Therefore, the calculated results can be used to support an assessment of seismically induced shear deformation around deposition holes.

However, the SKB approach for using the calculated results to assess seismically induced shear deformation relies on (i) the magnitude of seismically induced fracture slip versus distance from the source fault and (ii) the magnitude of seismically induced slip versus fracture size. Both of these relationships depend on the magnitudes of fracture slip that were calculated by the SKB analyses. The reviewers have identified four potential concerns that could affect the calculated slip magnitudes in the SKB analyses: (i) whether the ground motions due to the simulated fault slip events are sufficiently representative of ground motions due to potential earthquakes; (ii) whether the effects of potential coalescence of existing fractures during a seismic event are adequately accounted for in the calculated relationship between fracture size and magnitudes of induced slip; (iii) whether the calculated stress evolution (both temporal and spatial evolution of stress orientations and magnitudes) in the target fracture region explains the calculated fracture slip patterns; and (iv) whether the calculated patterns of induced slip would be significantly different if the modelled faults were blind faults (i.e., faults that do not intersect the ground surface).

3.1. Ground motion characteristics

The mechanical or structural effects of an earthquake arise from ground motions transmitted to a site during the earthquake and are controlled by ground motion characteristics such as magnitude and frequency of acceleration, velocity, or displacement. Therefore, the potential effect of an earthquake on a constructed structure or geologic medium is typically estimated by subjecting the structure or medium to seismic ground motions that are representative for the site. In contrast, the SKB analysis first simulated the fault failure mechanism for the potential earthquake and then calculated the response of the geologic medium to ground motions due to the simulated faulting. Therefore, an adequate case needs to be made that ground motions due to the simulated faulting are sufficiently representative of ground motions due to an earthquake that can occur at the site during the compliance period. SKB, in Figure 5-13 of TR–08–11 (Fälth et al., 2010), described a potential effect of the frequency content of ground motion on the calculated fault slip. The figure provides an example to illustrate that a fracture could slip within limited time intervals during a seismic event if the ground motion time history includes stress cycles with magnitudes sufficient to induce slip [see item (3) on list of SKB information summarized previously]. The ground motion magnitude and frequency content of the time history determine the stress magnitudes that may occur and the number and duration of stress cycles large enough to cause fracture slip. Therefore, the magnitude and frequency content of the applied ground motion time history could have significant effects on calculated fracture slip.

In Section 6.4 of TR–08–11 (Fälth et al., 2010), SKB provides a comparison of calculated velocity time histories against measured velocity time histories from the 1999 Chi-Chi earthquake and noted the following: (i) the calculated peak ground velocity is smaller than the peak ground velocity measured at two stations but it is close to the measured peak velocity at other stations; and (ii) the shape of the calculated velocity time histories is similar to the measured time histories at two stations. A systematic quantitative comparison of the calculated and measured ground motion magnitudes and frequency, which SKB did not provide, could have helped in confirming if the ground motion time history applied to the target fracture region is indeed representative of the ground motion time histories due to representative earthquakes. Alternatively, ground motion time histories that are considered representative for the site could be applied directly to a model of the target fracture region to assess potential induced slip.

3.2. Coalescence of existing fractures

Because the magnitude of induced slip correlates linearly with fracture size (Fälth et al., 2010), fracture coalescence during a seismic event may result in greater shear deformation than SKB assessed using the initial fracture size distribution. The model that SKB used to assess shear deformation due to induced fracture slip did not include fracture propagation or coalescence (Fälth et al., 2010). Indeed, a model that includes fracture propagation or coalescence likely will be impractical for such assessment. SKB stated in Section 6.8 of TR–08–11(Fälth et al., 2010) that energy consumption due to fracture propagation (if the model had included fracture propagation) would have resulted in smaller magnitudes of induced slip than were calculated. However, fracture coalescence could result in fracture sizes significantly larger than those used in the model and, therefore, slip magnitudes significantly greater than those that were calculated. The SKB information that an unstable stress condition persisted in fractures near the fault after the simulated seismic event suggests that the rock bridge at the end of such fractures could have failed during the seismic event if the simulated material model had permitted rock failure. Failure of a rock bridge could promote the coalescence of adjacent fractures.

Fracture coalescence could be an important rock failure mechanism where the existing fractures generally do not cut through the potential release boundaries (e.g., Shen et al., 1995; Trifu and Urbancic, 1996; Bobet and Einstein, 1998; Lee and Jeon, 2011). Fractures may coalesce if the existing stress condition in the rock bridge between the fractures can satisfy the applicable rock failure criterion for the bridge. Therefore, the effect of fracture coalescence could be assessed by joining non-through-going fractures in the discrete fracture network that are separated by rock bridges likely to fail when subjected to a representative ground motion time history for the site. Such analysis could result in a reduction in the total number of fractures but could also increase the magnitude of fracture shear displacement.

3.3. Transparency of stress state evolution

Based on the SKB documents that were available, the reviewers were unable to assess whether the calculated stresses are geologically reasonable for the modelled slip conditions on the primary fault. Because the basic interpretations of induced fracture slip are intimately tied to the changes in stress magnitudes and orientations within the target fracture zone, a more detailed description of both the spatial and temporal changes in stress state in the target fracture region is needed for a detailed evaluation of SKB's calculated slip patterns in the target fracture region.

3.4. Exclusion of blind faults

As noted in Chapter 4 in TR–08–11 (Fälth et al., 2010), SKB performed analyses using a model of an earthquake-generating fault that cuts through a zone of fractured rock and daylights at the ground surface. This geometry is referred to as an emergent fault. Many natural faults, however, are blind—they do not intersect the ground surface prior to or during earthquake rupture (e.g., Hauksson et al., 1995; Stein and Yates, 1989; Talebian et al., 2004). Some examples of recent large earthquakes that occurred on blind faults include the 1987 Whittier Narrows California earthquake, the 1994 Northridge California earthquake, the 1995 Kobe Japan earthquake, the 2003 Bam Iran earthquake, and the 2012 Dumaguete Philippines earthquake (e.g., Hauksson et al., 1995; Talebian et al., 2004). The resulting fault tip in the subsurface represents a displacement discontinuity that will lead to the development of complex stress and strain states in the overlying rock as the rock accommodates the decreasing displacement gradient. The details of this transition region, including the volumetric extent of affected rock as well as the spatial and temporal changes in stress magnitudes and orientations, will be controlled by the subsurface geology and by the displacement gradient along the fault (e.g., a gentle decrease in fault slip toward the tip versus a steep or abrupt decrease).

4. Recommendations

In the interest of conducting a detailed review of the SR-Site, SSM should consider requesting the following supplemental information from SKB regarding the SKB approach based on using sets of stand-off distance ranges and a critical fracture radius for each range to control the potential for damaging fracture slip during a seismic event. The additional information could be used to gain greater confidence in the SKB calculated values of critical fracture radius for the ranges of stand-off distance.

1. Provide information to show that ground motion time histories used for the analysis of target fracture behaviour are representative of ground motion time histories due to the representative earthquakes for the Forsmark site. The information could consist of (i) a systematic quantitative comparison of calculated and measured ground motion magnitudes and frequency or (ii) analyses performed using representative ground motion time histories applied directly to a model of the target fracture region.

2. Provide an assessment of the effects of potential fracture coalescence during a seismic event on fracture sizes and slip magnitudes of existing fractures. The assessment could be performed by evaluating the effects of joining non-through-going fractures that are separated by rock bridges likely to fail when subjected to ground motions due to a representative earthquake.

3. Provide a more detailed description of the spatial and temporal stress state evolution in the target fracture region. The temporal and spatial stress distributions control the induced slip on existing fractures in the target fracture region and, therefore, are needed to evaluate the calculated slip patterns.

4. Provide analyses that include a primary fault that is geometrically blind. The deformation gradients and stress state evolution in a fractured rock medium overlying a slipping blind fault could be significantly different from the SKB models and could lead to revised estimates of the induced slip patterns in the target fracture region.

In addition, the reviewers suggest that SSM consider conducting the following independent analyses to confirm SKB conclusions.

1. Examine potential failure of a rock bridge (relatively intact rock separating adjacent rock fractures) during a seismic event.

2. Evaluate the effects of a slipping blind fault on fracture stability and slip magnitudes in an overlying fractured rock.

5. References

Bobet, A. and H.H. Einstein. 1998. "Fracture coalescence in rock-type materials under uniaxial and biaxial compression." *International Journal of Rock Mechanics and Mining Sciences*. Vol. 35, No.7. pp. 863–888.

Fälth, B., H. Hökmark, and R. Munier. 2010. "Effects of large earthquakes on a KBS–3 repository: Evaluation of modelling results and their implications for layout and design." SKB TR–08–11. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company.

Hauksson, E., L.M. Jones, and K. Hutton. 1995. "The 1994 Northridge earthquake sequence in California: Seismological and tectonic aspects." *Journal of Geophysical Research*. Vol. 100. pp. 12,335–12,355.

Lee, H. and S. Jeon. 2011. "An experimental and numerical study of fracture coalescence in pre-cracked specimens under uniaxial compression." *International Journal of Solids and Structures*. Vol. 48. pp. 979–999.

Shen, B., O. Stephansson, H.H. Einstein, and B. Ghahreman. 1995. "Coalescence of fractures under shear stresses in experiments." *Journal of Geophysical Research*. Vol. 100, No. B4. pp. 5,975–5,990.

SKB, 2010. "Geosphere process report for the safety assessment SR-Site." TR–10–48. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company.

Stein, R. and R.S. Yeats. 1989. "Hidden earthquakes." *Scientific American*. Vol. 260. pp. 48–57.

Talebian, M., E.J. Fielding, G.J. Funning, M. Ghorashi, J. Jackson, H. Nazari, B. Parsons, K. Priestley, P.A. Rosen, R. Walker, and T.J. Wright. 2004. "The 2003 BAM (Iran) earthquake: Rupture of a blind strike-slip fault." *Geophysical Research Letters*. Vol. 31, No. L11611.

Trifu, C.-I. and T.I. Urbancic. 1996. Fracture coalescence as a mechanism for earthquakes: Observations based on mining induced microseismicity. *Tectonophysics*. Vol. 261. pp. 193–207.

APPENDIX 1

Coverage of SKB reports

Reviewed report	Reviewed sections	Comments
SKB TR–08–11: Effects of large earthquakes on a KBS–3 repository: Evaluation of modelling results and their implications for layout and design	All	
SKB TR–11–01: Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project	4, 10.2.2, 10.3.5, 10.4.4, 10.4.5, 15.5.6, 15.5.12,	
SKB TR–10–48: Geosphere process report for the safety assessment SR-Site	4	
SKB TR–08–05: Site description of Forsmark at completion of the site investigation phase: SDM-Site Forsmark	5, 7	
SKB TR–10–52: Data report for the safety assessment SR-Site	6.4, 6.5	

APPENDIX 2

Suggested needs for complementary information from SKB

1. Provide information to show that ground motion time histories used for analysis of target fracture behaviour are representative of ground motion time histories due to the representative earthquakes for the site. The Swedish Nuclear Fuel and Waste Management Company (SKB) selected model parameters to control characteristics of the simulated earthquake; such as moment magnitude, stress drop, and fault slip velocity; but did not provide a systematic analysis of the simulated ground motions to show how they may relate to the representative ground motions for a target repository site. Such analysis is requested because the mechanical effects of an earthquake are controlled by the magnitude and frequency of ground motion transmitted to a site due to the earthquake.
2. Provide an assessment of the effects of potential fracture coalescence during a seismic event on fracture sizes and slip magnitudes of existing fractures. SKB information indicates the simulated seismic events could cause failure of the rock bridge between fractures and, therefore, coalescence of such fractures. Because SKB relies on fracture slip scaling linearly with fracture size in deriving the critical fracture size for a given range of respect distance from an earthquake source fault, longer fractures due to fracture coalescence could imply a different assessment of slip magnitudes and critical fracture size for each respect distance range.
3. Provide a more detailed description of the spatial and temporal stress state evolution in the target fracture region. The occurrence of fracture slip in the target fracture region is closely dependent on the stress evolution. The requested information will help in evaluation of the calculated slip patterns.
4. Provide analyses that include a primary fault that is geometrically blind. Because the deformation gradients and stress state evolution in a fractured rock medium overlying a slipping blind fault could be significantly different from the simulated conditions in the target host rock region of the SKB model, the effects of a blind fault could lead to revised estimates of potential induced slip as a function of distance from a potential earthquake-source fault.

APPENDIX 3

Suggested review topics for SSM

1. Examine potential failure of a rock bridge (relatively intact rock separating adjacent rock fractures) during a seismic event. The results of such analysis will assist the Swedish Radiation Safety Authority (SSM) in evaluating any information provided by Swedish Nuclear Fuel and Waste Management Company (SKB) to address possible effects of fracture coalescence on slip magnitudes, critical fracture size, and respect distance from potential earthquake-source faults.
2. Evaluate the effects of a slipping blind fault on fracture stability and slip magnitudes in an overlying fractured rock. The results of such analysis will assist SSM in evaluating any information provided by SKB to address how the assessment of slip magnitudes, critical fracture size, and respect distance from potential earthquake-source faults may differ if the faults were blind.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se