RAI Volume 3, Chapter 2.2.1.3.2, Fourth Set, Number 1:

Explain how the cumulative effects of thermal stress and initial seismic events are considered in analyses of the extent of rockfall from multiple seismic events and affect repository performance.

Basis: In addition to forming a small amount of rockfall, DOE analyses show that a 10^{-4} seismic event creates block interfaces that have failed in shear or tension (e.g., BSC, 2004, Figure 6-120). Based on the DOE UDEC-Voronoi model calibration, such block failures should reduce the strength of the rock mass. However, an analysis of multiple 10^{-4} seismic events in a heated drift (BSC, 2004, Figure S-49) shows the same amount of rockfall as occurs in a single 10^{-4} seismic event in a heated drift (BSC, 2004, Figure S-47). DOE has not explained how the apparent weakening in rock strength from an initial seismic event, especially in the area close to the drift opening (e.g., BSC, 2004, Figure 6-120), stabilizes the rock mass such that no additional rockfall occurs during a subsequent seismic event. This result also does not appear consistent with caving relationships in BSC (2004, Figure 6-149), which show that caving potential increases as the hydraulic radius of the opening increases.

1. RESPONSE

1.1 APPROACH FOR ANALYSIS OF CUMULATIVE EFFECTS

Different loading scenarios were considered in the analysis of drift degradation in the lithophysal rock mass, including: (1) combined effects of thermally induced stresses and seismic events[1] with relatively high probability of exceedance (BSC 2004, Section 6.4.2.3.2) and (2) combined effects of time-dependent strength degradation, thermally induced stresses, and multiple seismic events (BSC 2004, Section S3.4.3). Only the relatively high probability seismic events with 10^{-4} probability of annual exceedance were considered, combined with the thermally induced stresses and the time-dependent strength degradation. Because the effect of stronger events (i.e., 10^{-5} or lower probability of annual exceedance) on the drift stability is much greater than the effect of thermally induced stresses and the time-dependent strength degradation, those loading conditions were not considered combined. For example, the events with 10^{-6} or lower probability of annual exceedance cause complete drift collapse in the lithophysal rock mass, so thermal stress or

1 The term "seismic event" in this response generally refers to the ground motion caused by an earthquake. In the context of postclosure seismic consequence analyses, the ground motion is typically characterized by the peak ground velocity (PGV) value of its first horizontal component. For a given value of horizontal PGV, the probabilistic seismic hazard analysis for Yucca Mountain, combined with ground motion conditioning and site-response modeling, gives a mean annual frequency with which the peak velocity value is expected to be exceeded (the bounded hazard curve). Seismic event rates refer, therefore, to ground motion exceedance rates rather than earthquake occurrence rates. For convenience, sets of three-component ground motion time histories are sometimes referred to in terms of their horizontal PGV value (e.g., 0.4 m/s PGV ground motions) or the mean annual frequency of the horizontal PGV value being exceeded (e.g., 10^{-4} ground motions).

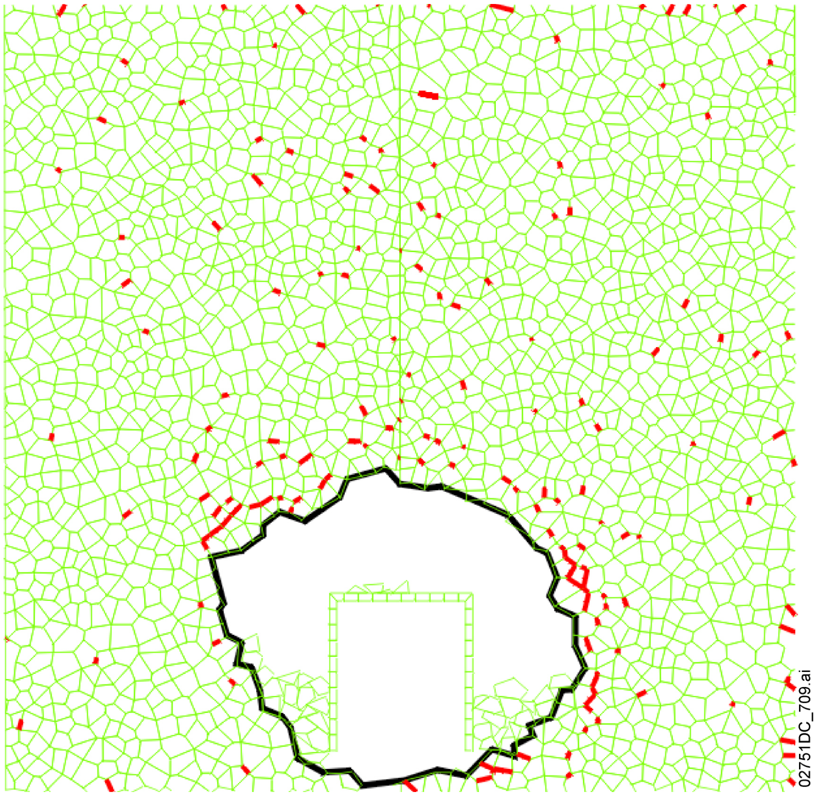
strength degradation would not significantly affect drift response (BSC 2004, Section 6.4.2.2.2.2).

The drift stability for seismic loading combined with thermal loading and time-dependent strength degradation is analyzed for 80 years (i.e., the time when the thermally induced stresses reach the maximum) and 10,000 years as the occurrence times of the seismic events. In the first step of the analysis, the evolution of damage and rockfall for thermally induced stresses and time-dependent strength degradation are simulated quasi-statically until the time of occurrence of the seismic event is reached. The second step of the analysis accounts for the dynamic effects of the seismic event. The initial state for the dynamic analysis is the equilibrium state that includes the stress state and the damage and rockfall from the model evolution up to the time of the seismic event. Thus, potentially weakened (damaged) lithophysal rock mass around the emplacement drifts due to the previous stress history is subjected to stress changes and inertial forces resulting from seismic ground motions. Seismic shaking can cause additional rockfall and/or damage of the rock mass depending upon: (1) the intensity of the seismic shaking, (2) the category of the lithophysal rock mass (i.e., strength and stiffness), and (3) the level of accumulated damage (a result of previous quasi-static stress and strength-degradation history).

1.2 EFFECTS OF 10^{-4} SEISMIC SHAKING ON DAMAGE IN LITHOPHYSAL ROCK MASS FOR *IN SITU* CONDITIONS

Previous analysis has shown (BSC 2004, Section 6.4.2.2.1 and Figure 1) that seismic ground shaking with 10^{-4} probability of annual exceedance for *in situ* conditions (i.e., ambient temperature and no time-dependent strength degradation) causes damage and rockfall in lithophysal rock mass Category 1 only. The main effect of seismic shaking in lithophysal rock mass Category 1 is to shake down already fractured and potentially loose rocks from the drift walls. The *in situ* stress concentrations in the drift walls exceed the strength of Category 1 lithophysal rock mass, resulting in damage and fracturing in the drift walls to a depth of 0.5 m (BSC 2004, Figure 7-26).

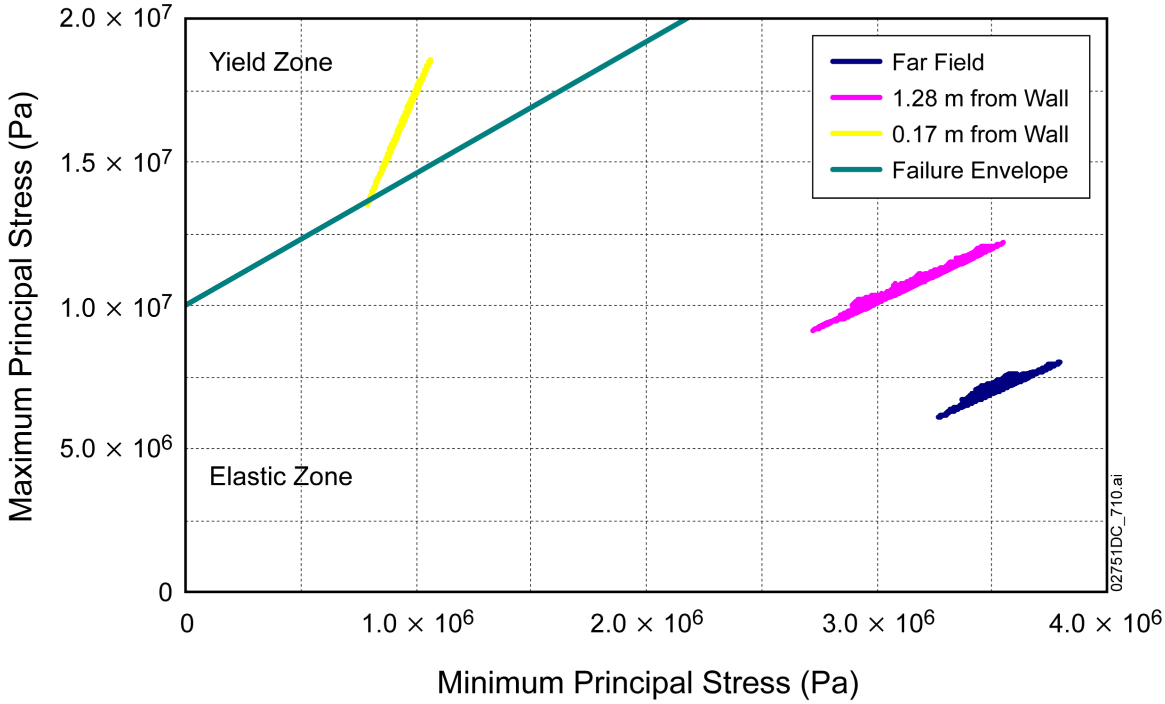
As shown in Figure 1, the 10^{-4} seismic events will shake down some of the loose rock from the walls. The same figure also indicates extension of the damage with development of the breakout. (The breakout is the change of the drift profile due to rockfall of the fractured rock. The extended damage caused by the breakout are the cracks around the breakout in the left wall, shown as red lines.) However, the elastic stress paths in the drift wall during a 10^{-4} seismic event compared to the yield surface for lithophysal rock mass Category 1, shown in Figure 2, indicate that the additional fracturing during shaking is not a consequence of seismically induced stress fluctuations or inertial forces. That is, stress oscillations are relatively small, and do exceed the yield surface at the points that are outside the yield surface under *in situ* conditions. The additional fracturing is a result of stress redistribution due to removal by shaking of the loose rock. The fractured and potentially loose rock under *in situ* conditions stays in place under quasi-static conditions prior to the first seismic event, providing some confinement and preventing further propagation of damage in the drift walls. When that loose rock is shaken down, the confinement is lost, resulting in additional damage in the form of loss of interblock cohesion (in red), as shown in Figure 1.



Source: BSC 2004, Figure 6-120.

NOTE: Red lines indicate block bonds (cohesion between blocks) that have failed in shear or tension.

Figure 1. Drift Outline and Damage after Simulation of 10^{-4} Ground Motion in Rock Mass Category 1



Source: BSC 2004, Figure 6-121.

Figure 2. Elastic Stress Paths in the Drift Wall Due to 10^{-4} Preclosure Ground Motion: Category 1

In lithophysal rock mass Categories 2 through 5, the analyses indicate that 10^{-4} seismic ground motion under *in situ* conditions causes no damage or rockfall (BSC 2004, Section 6.4.2.2.1). That observation is further confirmed by a series of analyses of drift stability at the 0.4 m/s peak ground velocity (PGV)[2] level (SNL 2007, Appendix C, Figure C-1). Those analyses show that only four realizations (different combinations of ground motion set and lithophysal rock mass category), all of which are for Category 1, result in some rockfall prediction. (The combinations of ground motion numbers and rock mass categories for different realizations from SNL 2007, Appendix C, Figure C-1, are listed in BSC 2004, Table 6-44.) No rockfall or damage is predicted in lithophysal rock mass Categories 2 to 5. Because lithophysal rock mass Category 1 is relatively sparse (BSC 2004, Section E4.1.3.2 and Figure E-10) and typically occurs within relatively small volumes (i.e., the drift stability model in which the entire drift is in lithophysal rock mass Category 1 significantly overestimates the continuous spatial extent of Category 1), it is expected that seismic ground motion at the 0.4 m/s PGV level or 10^{-4} probability of annual exceedance will not cause additional damage or fracturing in the lithophysal rock around the

[2] Stability of the emplacement drifts in lithophysal units during preclosure seismic ground motions has been analyzed and documented in Section 6.4.2.2.1 of *Drift Degradation Analysis* (BSC 2004). The analyses were carried out for two preclosure levels of annual probability of exceedance, 5×10^{-4} (the 0.19 m/s PGV level) and 10^{-4} (the 0.384 m/s PGV level). One three-component set of ground motion time histories was provided for each PGV level. In order to capture the effect of spectral content and the duration of time histories on rockfall prediction, the additional analyses were conducted (SNL 2007, Appendix C) for 15 ground motion sets at the 0.4 m/s PGV level, generated by rescaling the ground motions from the 1.05 m/s PGV level by the factor $0.4 /1.05 \approx 0.381$.

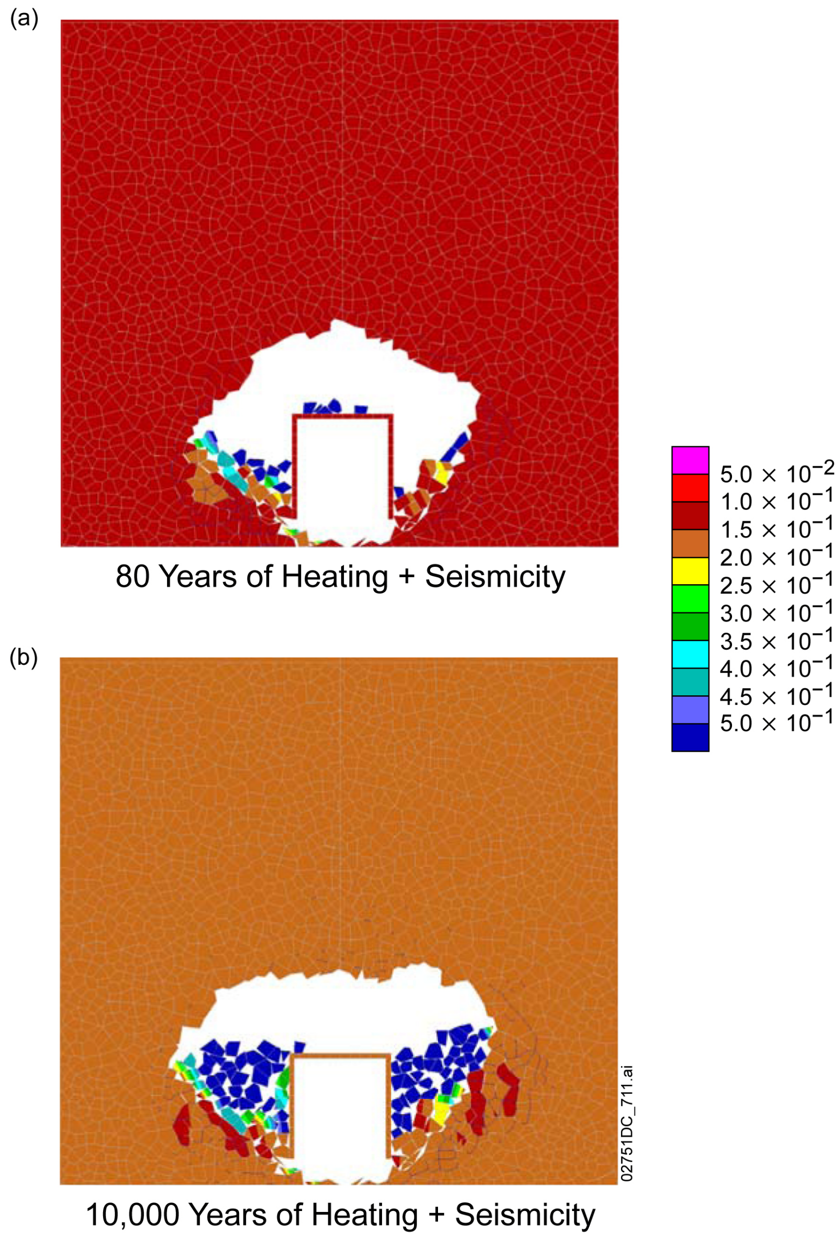
emplacement drifts. However, such ground motions shake down loose blocks created by fracturing due to thermally induced stresses (or time-dependent strength degradation) as shown by additional rockfall from the drift crown in Category 5 lithophysal rock mass after 80 years of heating (BSC 2004, Figure 6-145).

1.3 CUMULATIVE EFFECTS OF MULTIPLE LOADING CONDITIONS

The cumulative effect of combined thermal stresses, time-dependent strength degradation, and single and multiple 10^{-4} ground motions is analyzed for lithophysal rock mass Categories 2 and 5, representative of expected conditions in the repository (BSC 2004, Section S3.4.3). Lithophysal rock mass Category 1 was not analyzed because it represents a relatively small fraction (3%) of lithophysal rock mass (BSC 2004, Section 6.7.1.2) and does not occur in volumes large enough to encompass an entire emplacement drift. Thus, observations of fracturing in rock mass Category 1 in Figure 1 are not relevant for the results for Category 2 shown in Figures 3 and 4. In addition, the impact of a single seismic event on rock mass Category 5 caused only minor rockfall and no additional damage (BSC 2004, Figures S-46 and S-48). Thus, multiple seismic events for rock mass Category 5 were not analyzed.

Multiple seismic events were considered occurring shortly after 80 years and 10,000 years. The states at those two times bound the stresses (relatively large at 80 years compared to 10,000 years) and damage due to time-dependent strength degradation (gradually increasing with time) of the rock mass around the emplacement drifts during the entire 10,000 year period. Thus, the effect of multiple seismic events at intermediate times will be bounded by the effects of the multiple seismic events after 80 years and 10,000 years. When the results are compared for a single and two successive seismic events after 80 and 10,000 years, as shown in Figures 3 and 4, it is obvious that the second seismic event after 80 years causes additional rockfall, while after 10,000 years it does not. However, even when the second event results in additional rockfall, it is relatively small. Because the first two 10^{-4} seismic events shake down loose, fractured rock mass, but do not cause new damage of the rock mass, the subsequent events of the same severity will not cause additional rockfall (and, therefore, were not analyzed).

After 80 years, the damage and stress state in the rock mass are such that a single event is insufficient to shake down all of the fractured or loose rock mass. At this time, stresses in the crown are greater than after 10,000 years, providing more confinement and frictional resistance. Consequently, there is additional rockfall after the second seismic event. However, after 10,000 years, the first event shakes down all fractured rock and subsequent events do not cause any additional damage or rockfall.



Source: BSC 2004, Figures S-45 and S-47.

NOTE: A residual, rigid body translation of the model occurred because the dynamic simulation was stopped before the end of the ground motion was reached.

Figure 3. Effect of 10^{-4} Ground Motions in Category 2: Contours of Displacement (m)