**RAI Volume 3, Chapter 2.2.1.2.1, Second Set, Number 19, Supplemental Question 4:**

> What is the lateral and vertical extent of the volume of rock that is likely to contribute to a seismically induced water table rise? For example, Montgomery and Manga in Science 2003 indicate that changes in ground water levels for a 6.5 magnitude earthquake may be measurable up to 100 km or more from the epicenter.

## 1. SUPPLEMENTAL RESPONSE

Persistent, seismically induced changes in water table elevation have been modeled by poroelastic response of the earth's crust following an earthquake (e.g., Roeloffs 1996). In this model, volumetric strain caused by earthquake-related changes in mean compressive stress affects pore fluid pressure. The change in pore pressure can be manifested as a change in water table elevation depending on the properties of the hydrologic system. The volume of rock experiencing earthquake-related volumetric strain defines the volume that contributes to a potential change in water table elevation. This volume is variable. Its spatial distribution and amount is a function of the type of faulting, amount of slip, fault geometry, and the mechanical properties of the rock. Volumetric strain for a normal-faulting earthquake is largest at depth near the bottom of the fault and generally diminishes with distance from the fault (e.g., Carrigan et al. 1991, Figure 1; National Research Council 1992, Appendix D, Figure 2). Roeloffs (1996, p. 155) notes that water table effects due to earthquake-related changes in mean compressive stress might be expected up to a distance equal to a few source dimensions from the epicenter, with effects diminishing with distance.

Expanded evaluations of the potential for earthquake-induced water table rise at Yucca Mountain in the response to RAI 3.2.2.1.2.1-2-019 and Supplemental Question 6 were based on a poroelastic model representation developed by Kemeny and Cook (1990, 1992). Kemeny and Cook (1990, pp. 5-14 to 5-17) introduce a series of conservative assumptions that reduce the coupled hydro-mechanical poroelastic model to a simplified mechanical representation. This representation relates water table rise to earthquake static stress drop and the vertical extent of the earthquake-related faulting (Kemeny and Cook 1992, Equation 6-1). They assume that the volume of rock likely to contribute to a seismically induced water table rise is defined by the length of the fault ($L$), the vertical extent of faulting ($h$), and a lateral distance on both sides of the fault equal to the vertical extent of faulting (a total width of $2h$). In the final Kemeny and Cook representation (Kemeny and Cook 1992, Equation 6-1), the vertical extent of faulting ($h$) is the only component of the affected volume that enters the calculation of water table rise.

Because earthquake-related changes in volumetric strain extend laterally away from a fault, faults within a source dimension or two of the waste emplacement area also can potentially cause a change in water table elevation beneath Yucca Mountain. Thus, in expanding the assessment of potential earthquake-induced water table rise for Yucca Mountain in response to Supplemental Question 6, faults within about 20 km of the site were included. These faults were defined as "local" by the seismic source characterization expert teams in the probabilistic seismic hazard analysis (PSHA) (CRWMS M&O 1998, Figures 4-18, 4-28, 4-38, 4-48, 4-56, and 4-65). A vertical extent of faulting up to 15 km was considered for local faults, again based on

interpretations of the PSHA seismic source characterization teams (CRWMS M&O 1998, Table 4-1). Therefore, the vertical and lateral extent of the volume of rock that is likely to contribute to water table rise at Yucca Mountain is determined by the fault dimensions (length, width, and depth) of the earthquake sources being evaluated and has been appropriately taken into account in response to Supplemental Question 6.

Whether an increase in pore pressure resulting from the poroelastic response to an increase in mean compressive stress contributes to a water table rise depends in part on the properties of the hydrologic system. The literature associated with earthquake-induced poroelastic deformation and associated hydrologic responses generally relates to observed water level changes in open boreholes. Groundwater level changes may be associated with changes in hydraulic head when a well is open to a confined aquifer(s) or to water table elevation changes when the well is open to an unconfined aquifer. When wells are open to multiple aquifers, the water level in the well will be controlled by the hydraulic head in the most transmissive unit(s) intersecting the well. Such observations indicate that earthquake-induced groundwater level changes in confined aquifers are greater than water table elevation changes in unconfined aquifers (Manga and Wang 2007, p. 302; Koizumi et al. 2005).

The reason for the greater amplitude of response of the water level in confined aquifers is the result of the smaller storativity of confined aquifers. Considering a given poroelastic compression with the resultant volume of water released per unit surface area of the aquifer, the smaller storativity of the confined aquifer will result in a higher water level rise in boreholes that are open to the confined aquifer. In the vicinity of Yucca Mountain, the Death Valley Regional Groundwater Flow Model has estimated the specific storage (storativity divided by thickness) of confined aquifers of between $10^{-7}$ and $10^{-4}$ $m^{-1}$ and a specific yield of unconfined aquifers of about 0.2 (Belcher 2004, Figure F-38). Assuming a confined aquifer thickness of about 100 m leads to a storativity of between about $10^{-5}$ and $10^{-2}$. This storativity value range is between 0.005% and 5% of the specific yield value (0.2). Therefore, an earthquake capable of causing a water level rise of 100 m in the confined aquifers at Yucca Mountain would be expected to cause only a 0.005 to 5 m rise in the water table.

The distinction between water level rise and water table rise becomes relevant when confining units separate the aquifers. If there are no confining units, the water table response will be equal to the water level response to the poroelastic deformation. This is the conservative assumption made by Kemeny and Cook (1990, 1992) when they reduced the coupled hydro-mechanical response to a simple mechanical representation in which hydraulic head changes at depth were assumed to be immediately propagated to water table elevation changes. In assuming there were no confining units, Kemeny and Cook effectively assumed that the water volume released by the compression of the entire saturated thickness of rock (about 10,000 m) would be available for raising the water table. Observations of water level and water table elevation changes noted earlier, combined with the known confining units in the saturated zone in the vicinity of Yucca Mountain, confirm that this is a conservative assumption.

In addition to hydrologic effects due to earthquake-related changes in mean static stress, hydrologic effects are also observed from dynamic strains associated with propagation of seismic waves. Montgomery and Manga (2003, Figure 2) compile data showing that hydrologic effects

are documented at hundreds to thousands of kilometers from the earthquake source. Because earthquake-related changes in static stress in the far-field (beyond a few source dimensions) have amplitudes near zero (comparable to or less than stresses induced by non-seismic sources such as tides and barometric pressure changes), earthquake-related changes in water level in the far-field are considered to be caused by cyclic dynamic strains associated with passing seismic waves (Manga and Wang 2007, p. 305). Short-lived effects (minutes) have been explained in terms of cyclic volumetric strains associated with passing Rayleigh waves (Manga and Wang 2007, Section 4.10.3.1.1). More persistent effects (days, months) indicate changes to hydrologic properties caused by cyclic dynamic strains. Mechanisms such as consolidation and changes in fracture properties have been examined as causes of persistent far-field water level responses (Manga and Wang 2007, p. 305). For Yucca Mountain, earthquake-induced changes in hydrologic properties from such mechanisms are excluded from the total system performance assessment based on low consequence (SNL 2008, FEP 2.2.06.01.0A, Seismic Activity Changes Porosity and Permeability of Rock; FEP 2.2.06.02.0A, Seismic Activity Changes Porosity and Permeability of Faults; and FEP 2.2.06.02.0B, Seismic Activity Changes Porosity and Permeability of Fractures). Therefore, earthquake-related changes in hydrologic properties in the far-field, such as those documented by Montgomery and Manga (2003), are not pertinent to defining the vertical and lateral extent of the volume of rock that is likely to contribute to a seismically induced water table rise.

In summary, the vertical and lateral extent of the volume of rock that is likely to contribute to a seismically induced water table rise at Yucca Mountain is determined by the extent of volumetric strains associated with an earthquake. Such strains are largest within about a source dimension of the fault and depend on type of faulting, amount of slip, fault geometry, and the mechanical properties of the rock. Using the simple representation of a poroelastic model by Kemeny and Cook, for a given earthquake static stress drop, water table rise is proportional to the vertical extent of faulting. In response to Supplemental Question 6, the volume of rock likely to contribute to water table rise at Yucca Mountain is taken as extending laterally about 20 km from the site and to a vertical depth of up to 15 km.

## 2. COMMITMENTS TO NRC

None.

## 3. DESCRIPTION OF PROPOSED LA CHANGE

None.

## 4. REFERENCES

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