CONSTRAINTS ON EXTREME GROUND MOTIONS AT LOW PROBABILITIES

Brune, James N., Seismological Laboratory, University of Nevada, Reno, NV 89557, USA, brune@seismo.unr.edu

ABSTRACT

Probabilistic seismic hazard analysis (PSHA) makes statistical assumptions which are very questionable when extended to very low probability maximum ground motions (the order of 10 g acceleration and10 m/s velocity, with 10-6 to 10-8 annual probabilities. The short historical database for instrumental recordings is not sufficient to resolve the uncertainties in the statistical assumptions. This suggests that we look for geomorphic and geologic evidence constraining ground motions over long periods in the past. Since the extrapolated ground motions are so large we might expect to find evidence for them if they have occurred in recent geologic time. Such evidence might include lack of precariously balance rocks (10 ka to 100 ka), rock avalanches from formerly unstable cliff's (a few hundred ka), strain-shattered rock (up to tens of millions of years), and motion along ancient cracks (up to ten million years). A critical question for low-probability PSHA is: can the lack of any or all of these indicators be used as reliable evidence that such high ground motions have not occurred over periods from tens of thousands to tens of millions of years? Related critical questions are: can statistical evidence from the San Andreas Fault, where some rocks have been subjected to tens of thousands of M~8 earthquakes, be applied to other tectonic regimes such as Yucca Mountain, or to thrust regimes? Can indirect evidence from shattering of rocks on the hanging walls of thrusts in Southern California, and lack of such shattering in other areas, be used to constrain ground motions?

PRECARIOUS ROCK CONSTRAINTS ON EXTREME GROUND MOTIONS

As a result of the discovery of numerous precariously balanced rocks in the vicinity of Yucca Mountain, a methodology was developed to use these rocks as constraints on the probable ground motion to be expected at the potential repository. The precarious rock methodology gives a direct indication of the upper bound on the amplitude of past ground shaking at a site (in contrast to the indirect inference provided by trenching studies, which cannot directly constrain characteristics of ground motions associated with observed fault slip evidence).

In many types of terrain in California and Nevada, groups of precariously balanced rocks have evolved naturally by erosion. The common presence of rock varnish on such rocks indicates that they have been in their current unstable positions for thousands of years. Therefore, groups of precariously balanced rocks can be used as low-resolution strong-motion seismoscopes that have been operating on solid rock outcrops for thousands of years. As such, they provide important information about seismic hazard at low annual probabilities. We have established the mechanical basis for estimates of the horizontal accelerations necessary to topple precarious rocks, using field observations and numerical and physical modeling (Anooshepoor et al., 2004). The distribution of precarious rocks relative to known active faults and intensity zones produced by historical earthquakes confirms their usefulness in outlining areas that have or have not undergone recent strong ground shaking (Brune, 1996; 1999; 2002 a,b; 2004; 2005).

We evaluated estimates of peak acceleration made from observations of precarious or toppled rocks at the Nevada Test Site (NTS). We improved our estimates by field-testing of rocks and by using observed waveforms of nuclear explosions in our shake table tests. Theoretically predicted values of ground motion were calculated from existing attenuation relations for nuclear explosions. In general the results confirm our estimates of ground motion based on precarious rocks (Brune *et al*. 2003).

The relatively large horizontal ground accelerations predicted by the recently completed Yucca Mountain Probabilistic Seismic Hazard Analyses (PSHA, Stepp et al., 2001)) are not consistent with the preliminary results from the precarious rock survey conducted by Brune and Whitney (2000), nor the results described in the DOE Task 6 final report (Anooshehpoor *et al.*, 2002). Therefore, further development of the precarious rock methodology may provide important constraints on the statistical assumptions which lead to extremely high ground motion predictions at very low probabilities.

Cosmogenic Age Dating of Precarious Rock Pedestals

We have carried out preliminary determinations of cosmogenic age dates of precarious rock pedestals in Solitario Canyon (Brune, Whitney and Zreda, unpublished results, presented at DOE sponsored conferences). The cosmogenic age dates for precarious rock pedestals all exceed previous estimates (Bell et al.. 1998) based on rock varnish. This is not unexpected, since the rock varnish dates are minimum dates (because the rock varnish formation process can be "reset' by periods of intense weathering, as might be expected during ice ages). Cosmogenic pedestal age dates range from about 36 ka to 250 ka, with most values about 50-100 ka. These are considerably higher than the minimum dates from rock varnish (generally ~10.5 ka). Although we have not fully analyzed the implications for seismic hazard, these dates are consistent with the idea that no large ground motions (greater than about 0.3 g) have occurred since before the most recent large event proposed from trenching studies (about 70 ka ago on the Solitario Canyon fault and about 90 ka on the Paintbrush Canyon fault).

We need to further quantify precarious rock constraints on ground motion, especially for ground motion parameters other than PGA, for example, PGV (peak ground velocity), and response spectrum at various periods.

Lack of Data from the Hanging Wall of Normal Faults

The seismic hazard at the repository site, at very low probabilities, is determined primarily by the Solitario Canyon fault, which is immediately adjacent to the site. However, some of the hazard also comes from the Paintbrush Canyon fault (Most Recent Earthquake, MRE, 90 ka). The repository is on the footwall of the Solitario Canyon fault but on the hanging wall of the Paintbrush Canyon fault. There is abundant precarious rock evidence that the ground motion on the foot wall of normal faults is considerably lower than predicted by standard attenuation curves (Brune, 2000, 2003; Shi et al.,), consistent with the precarious rock evidence from Yucca Mountain. Numerical and physical modeling confirms that low ground motion is expected on the foot wall of normal faults (Brune and Anooshepoor, 1999; Shi et al., 2003)

However, there is very little precarious rock evidence constraining the ground motion on the hanging wall of normal faults. This is primarily because for most normal faults the hanging wall is covered by sedimentary fill (alluvium) to a distance of several km or more from the fault trace, so there is no exposed bedrock to form precarious rocks. Yucca Mountain is an exception because the fault slip rate on the Paintbrush Canyon fault is so slow that a deep sedimentary basin has not formed on the hanging wall. There are a few cases where river erosion has been fast enough to expose rocks on the hanging wall of active faults with Recent (Holocene) earthquakes (e.g., normal faults near the Carson and Walker Rivers). However these areas have not been studied in detail. Preliminary reconnaissance surveys have indicated that there are some exposures of rocks (of the types which form precarious rocks) at these sites. It is important to obtain any available precarious rock evidence constraining the ground motion at these sites. This might help confirm the direct evidence at Yucca Mountain that the last event on the Paintbrush Canyon fault (MRE 90 ka) has not caused intense ground shaking at the repository site.

UNSTABLE CLIFFS IN THE VICINITY OF YUCCA MOUNTAIN

In addition to numerous precarious and semi-precarious rocks in the vicinity of Yucca Mountain, there are numerous unstable cliff faces with numerous loose rocks stacked on top of each other. Such cliffs are common throughout the area, a result of differential erosion of welded and unwelded tuffs (Brune and Whitney, 2000). These cliffs appear to be obviously unstable with regard to horizontal ground shaking. That this is so in fact is demonstrated further north in NTS where the cliff faces have been shaken down by ground motion from nuclear explosions (Brune et al, 2003). Very near large NTS explosions, there are no precarious rocks. Cliff faces are shattered and numerous recent rockfalls and rock avalanches are evidenced by fresh white surfaces covered by caliche (calcium carbonate), clear indication that the rockfalls have been caused by the explosions. The caliche will dissolve off the rocks in a few hundred years. As the distance from the explosions increases, rock avalanches disappear and less and less rockfalls are observed. Keefer (1984) associates rock avalanches with intensities of roughly VIII (accelerations of roughly 0.30 to 0.5, or greater), rockfalls with intensities of roughly VI to VII (accelerations of roughly 0.05 g to 0.2 . Thus lack of evidence of rock avalanches is a constraint on extreme ground motions over the time period necessary to remove the evidence of such avalanches (typically a pile of rubble at the base of the cliffs and shallower cliff slopes).

The 1992 Richter local magnitude (M_L) 5.6 Little Skull Mountain (LSM) earthquake, located about 20 km southeast of Yucca Mountain confirms the rough relationship of horizontal ground acceleration with rockfalls and rock avalanches. The earthquake caused a number of rockfalls on steep cliff faces in the near-source region, but no rock avalanches, while some precarious rocks remained in place (Brune and Smith, 1996, Brune et al., in press, 2005)). The,. rockfalls were easily recognized by the presence of white carbonate and silicate left exposed on the faces of blocks broken away from the cliff face just as in the case of the NTS rockfalls, --otherwise, the rocks are universally covered with a very dark rock varnish. This contrast allows easy recognition of rockfalls along the crest of LSM. The fact that ground motion was sufficient to cause some rockfalls and yet leave semi-precarious rocks in place yields both upper- and lower-bound estimates on the ground motion at LSM, both during and prior to the earthquake, and these estimates are consistent with the ground motion estimates from NTS explosions.
Thus a useful constraint on strong ground motion at Yucca Mountain may be obtained by estimating the time it would take for shaken down cliffs, with consequent piles of rubble at their base, to be re-eroded to their current unstable conditions (no rubble at the base of the cliffs, many

unstable stacks of rocks). Preliminary estimates based on cosmogenic age dating described above, suggest times of the order of 100 ka

CONSTRAINTS FROM UNFRACTURED SANDSTONES ALONG THE SAN ANDREAS FAULT

Constraints on rare ground motions may be provided by sandstones located along the San Andreas fault at several locations between Tejon Pass and Cajon Pass (Brune et al., 2004) These sandstones are as old as or older than the San Andreas fault and thus have been exposed to San Andreas earthquakes for about 5 million years. At the current inferred rate of occurrence of large earthquakes this might translate into about 20,000 M+ 8 events,-- enough to provide statistical constraints at very low probabilities. Assuming that the ground motions for M~7 events at Yucca Mountain are less than or comparable to ground motions for M~8 events on the San Andreas fault (a very secure assumption), this corresponds to a constraint for an annual probability of 10-8 at Yucca Mountain.

Preliminary measurements of tensile strength of the San Andreas sandstones indicate values of less than 10 bars. If these values correspond to the true tensile strength of rocks in bulk at depth, over the history of the rocks, they provide constraints on very rare ground motions. At some sites about 1 km of the sandstone sections has been exposed by tilting and folding. At most sites at least 30 m of exposure has been created by erosion in canyons. Detailed studies of the sandstones have indicated that at some time in the past they may have been buried at least 1 km.

Very large vertical accelerations, over 3 g, would be expected to spall the rocks at a depth of about 20 m. No evidence of such spalling is observed. Internally, if the particle velocities exceed about 1 m/s at about ¼ wavelength depth, the internal strains would fracture the rocks in tension. Again, there is no evidence of such fracturing. The inferred upper limits on ground motion are consistent with the current (~50 year sample) instrumental strong motion data set, but in addition suggest that very much larger ground motions have not occurred over the 5 ma history of the San Andreas fault.

Confirmation of these constraints on ground motion will require: (1) further testing of the tensile strength of these rocks from samples further from the weathered surface, (2) accurate measurement of shear velocities, (3) accurate calculation of stresses from various ground motion waveforms, (4) further demonstration that no fractures exist, and (5) accurate detailed local geologic mapping to verify the depths of the sandstones as a function of time.