

# **PHYSICAL CONSTRAINTS ON UPPER BOUND GROUND MOTIONS**

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## **INTRODUCTION**

We examine two physical conditions that may place constraints on the upper bound levels of ground motions. First, we describe observations of weak ground motions from shallow faulting earthquakes. We also note that near-fault peak velocities may be bounded by the magnitude scaling of the period of the rupture directivity pulse. We then proceed to describe kinematic simulations of upper bound ground motions, using the inverse correlation between two strongly influential parameters, rupture area and rise time for a fixed magnitude event, to place bounds on the ground motions. We summarize the implications of these results for upper ground motions at Yucca Mountain, and suggest topics for further research.

## **REDUCTION OF GROUND MOTIONS FROM SHALLOW FAULTING**

Earthquakes typically nucleate near the bottom of the seismogenic rupture zone in the crust. Large earthquakes usually break the surface, but small earthquakes usually do not. Over one-half of the earthquakes in the magnitude range of 6.0 to 6.5 do not break the surface; this fraction decreases to about one-third for the magnitude range of 6.5 to 7, and about one-fifth of earthquakes in the magnitude range of 7.0 to 7.5 (Lettis et al., 1997). If it is assumed that all of the slip on a fault occurs during earthquakes, then larger earthquakes are characterized by relatively larger amounts of shallow slip than are smaller earthquakes.

These differences in the depth distribution of slip are important, because it appears that the ground motions generated by earthquakes that do not have large shallow asperities are stronger than those of earthquakes that do. Recent large earthquakes having large surface slip, including the 2002 Denali, 1999 Kocaeli, and 1999 Chi-Chi events, have surprisingly weak ground motions at short and intermediate periods. These new observations are consistent with our finding from previous earthquakes that the strong ground motions of earthquakes that have shallow asperities (top of asperity is shallower than 5 km) are weaker than the ground motions of events whose asperities are all deep (Kagawa et al., 2004; Somerville, 2003). The large differences in ground motion levels between these two categories of events are illustrated in Figure 1, which shows the response spectra of near-fault recordings of recent large earthquakes. The left panel shows recordings from four shallow earthquakes in the  $M_w$  range of 7.4 to 7.9, and the right panel shows recordings from two deep earthquakes of magnitude  $M_w$  6.7 and 7.0. The response spectra of the deep earthquakes are much stronger than those of the larger shallow earthquakes for periods less than 1.5 sec.

Comparing the distribution of slip with depth, averaged along strike, in the top part of Figure 2, this difference in ground motions between shallow and deep events seems paradoxical because the shallow events have much larger near-surface displacements. However, slip velocity is a much more important determinant of strong motion levels than fault slip alone. The effective slip velocity is defined by Ishii et al. (2000) as the slip velocity averaged over the time in which the slip grows from 10% to 70% of its final

value, and represents the dynamic stress drop. As shown in Figure 3, the distribution of effective slip velocity with depth for shallow events is quite different from the distribution of slip with depth. The shallow events have large near-surface displacements, but they do not have correspondingly large slip velocities. The slip velocities of the deep events are larger than those of the shallow events, causing larger ground motion levels because slip velocity is an important determinant of strong motion levels. Averaged over 9 shallow events and 8 deep events, the slip velocity of shallow events is about 70% that of deep events. This is true both for the fault as a whole and for the asperities on the fault. This difference in slip velocity between shallow and deep events is an important aspect of earthquake source characterization for the simulation of strong ground motion. For a given seismic moment, the rupture areas of shallow events are larger, and hence their static stress drops and smaller, than those of deep events, which may also contribute to the difference on ground motions (Kagawa et al., 2004).

The fracture energy and stress intensity factor are found to be large for surface faulting events, and small for subsurface faults. Large fracture energy events may produce mainly long period seismic radiation. This is consistent with surface faulting events producing weak high frequency ground motions. The features of rupture in the shallow part of fault (0 – 5 km depth) are controlled by velocity strengthening, with larger slip weakening distance  $D_c$ , larger fracture energy, i.e. much energy absorbed from the crack tip, lower rupture velocity, lower slip velocity, and lower ground motions than buried faulting events.

#### **ESTIMATES OF UPPER BOUND GROUND MOTIONS IN THE PEGASOS PROJECT**

We performed kinematic strong motion simulations based on earthquake source models that use the source scaling relations of Somerville et al. (2001) for the central and eastern United States. In order to establish the upper limit ground motion level, we considered three earthquake mechanisms and performed a large number of ground motion simulations. For each event, parametric uncertainty in a set of source characteristics was applied using multiple representations. The source parameters that were varied include slip model (s), depth (d), rupture area (ra), slip contrast (sc), hypocenter location (hy), rupture velocity (rv), rise time (rt). Where single parameter values were involved, the randomness was represented using median (M), upper (U), and lower (L) bound values; these variations (e.g. Urt) are indicated along the horizontal axis of Figure 4. The effect of each source parameter on the ground motion was evaluated based on simulations in which one of these parameters was varied while the others were kept fixed at their median value. Median ground motion values were derived from simulations that used median values of the source parameters. Upper limit values of ground motions were derived from simulations that used combinations of upper bound values of source parameters that most strongly affected the ground motion. The rupture area and rise time as well as their combination with supershear rupture velocity most strongly affect the ground motion level over a broad frequency range. The combination of extremely small rupture area and short rise time gives rise to extremely large ground motions.

Constraints were placed on upper bound ground motions based on correlation of source parameters. The two source parameters that have the strongest influence on ground motions, rupture area and rise time, have an inverse correlation. Combinations of

small rupture area and short rise time (Max2 in Figure 4) give rise to very large ground motions that are considered unphysical, because the small rupture area requires a large average displacement, which should be accompanied by a longer than median rise time, not shorter than median rise time. An even more extreme (and unphysical) set of scenarios adds supersonic rupture velocity to this combination of parameters (Extreme in Figure 4). These scenarios use combinations of small rupture area, small rise time, and super shear rupture time, together with the maximizing values of the other parameters (upper slip contrast, subsurface fault and reverse faulting mechanism). Because of the extremely low joint probability of occurrence of all of these extreme source parameters, we regard them as being unphysical.

## **PHYSICAL FACTORS LIMITING GROUND MOTIONS AT YUCCA MOUNTAIN**

### **Shallow Faulting**

Shallow faulting has low slip velocity and hence lower ground motions than buried faulting. We need separate ground motion models for shallow and buried faulting. These models might each have lower aleatory variability, and the shallow faulting model will have much lower median values. Ground motion amplitudes from shallow faulting earthquakes may have been overestimated in the Yucca Mountain PSHA

### **Rupture Directivity**

Upper bound ground motions at Yucca Mountain are controlled by rupture directivity effects. The amplitude of the directivity pulse is controlled by the rupture velocity, which is limited to the Rayleigh wave velocity or to supershear values. The period of the pulse increases with magnitude, bounding the magnitude scaling of the peak velocity of the directivity pulse (Somerville, 2003).

## **SUGGESTIONS FOR FUTURE RESEARCH**

### **Rupture Dynamics**

- Use rupture dynamics to establish a physical basis for differences in source parameters between shallow and buried faulting earthquakes
- Examine correlation between source parameters such as rupture velocity and rise time in kinematic and dynamic rupture models of past earthquakes, including normal faulting earthquakes
- Develop the capability to model differences in ground motions between shallow and buried earthquakes
- Use dynamic rupture models of normal faulting earthquakes to identify physical bounds on source parameters and ground motions

### **Probabilistic Seismic Hazard Analysis**

- Identify the depth of faulting of earthquakes on the Solitario Canyon fault
- Use separate ground motion models for shallow and buried faulting in YM PSHA
  - lower median value for shallow faulting
  - lower variability about the median for both shallow and buried faulting

- This may result in a reduction of this fault's contribution to the hazard at low probabilities

## Wave Propagation

- The Yucca Mountain volcanics constitute a basin-like environment – trapping of body waves that enter the volcanics from their margins
- Triplications, caustics and focusing effects can potentially cause large amplification of ground motions
- Look for evidence of amplification or deamplification in Yucca Mountain strong motion recordings from local and regional earthquakes and NTS events

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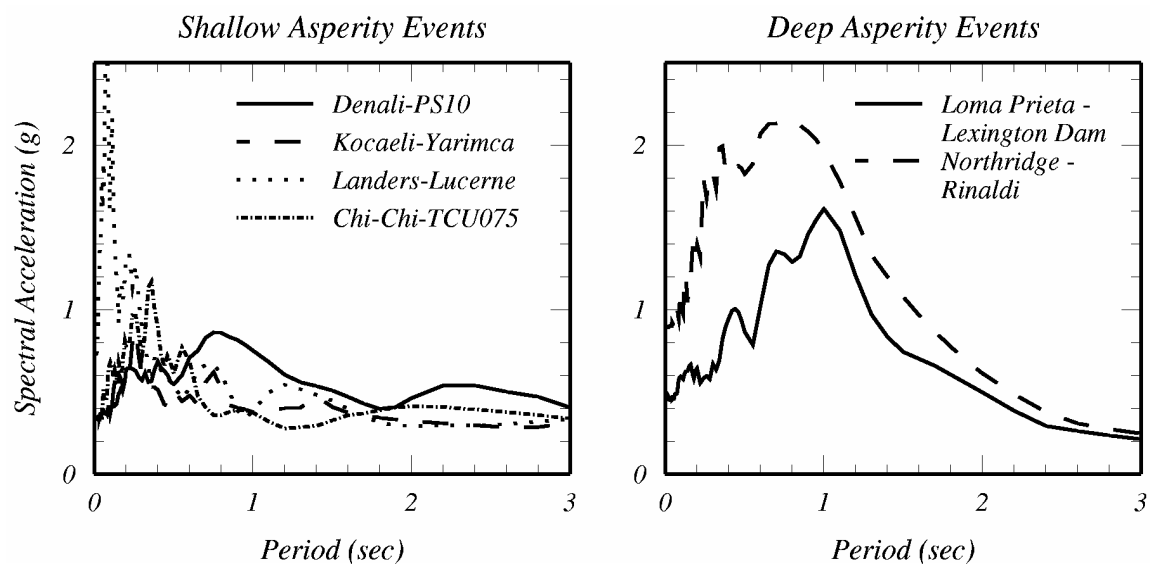


Figure 1. Near-fault response spectra of recent large earthquakes. Left: Four earthquakes, Mw 7.2 to 7.9, with shallow asperities and large surface faulting. Right: Two earthquakes, Mw 6.7 and 7.0, with deep asperities and no surface faulting.

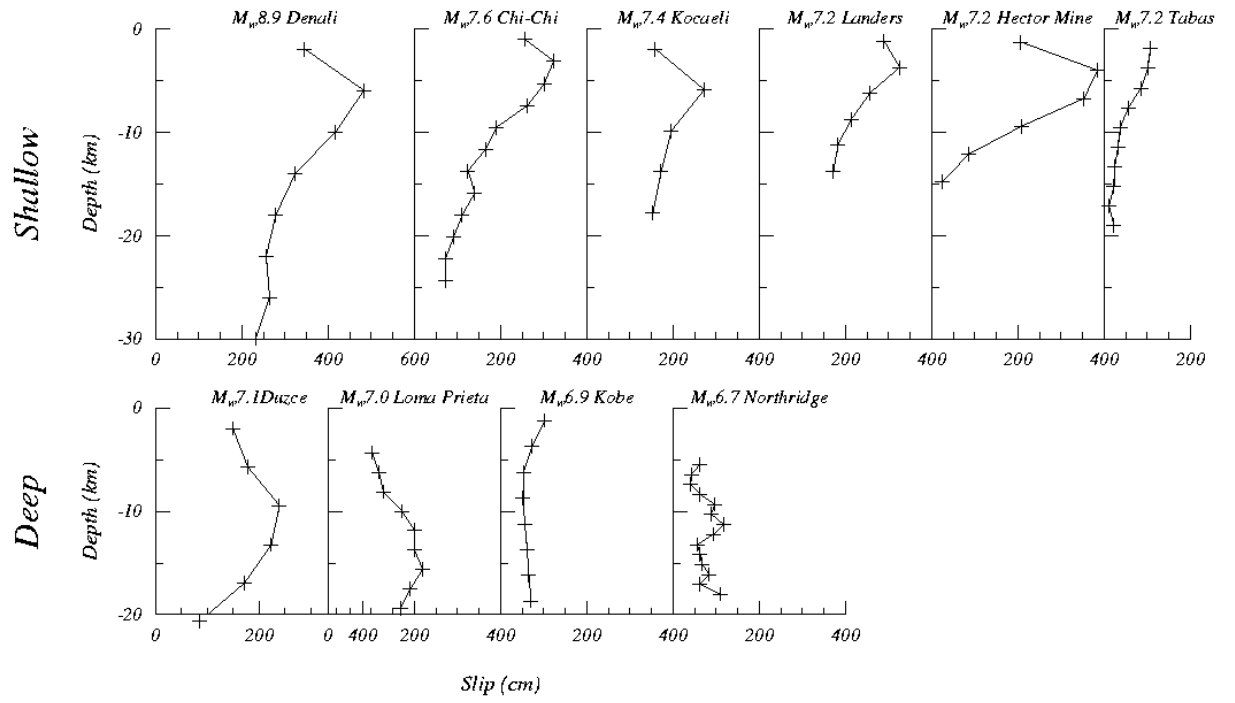


Figure 2. Distribution of slip for shallow (top) and deep (bottom) earthquakes.

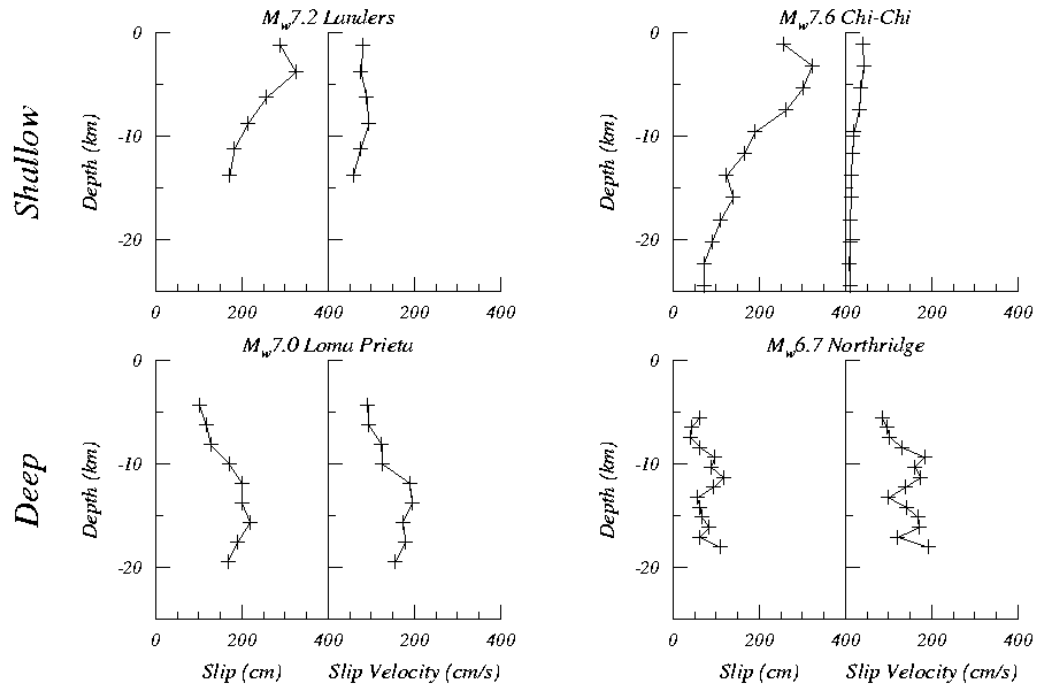


Figure 3. Distribution of slip (left) and slip velocity (right) for shallow (top) and deep (bottom) earthquakes. The left side shows two strike-slip earthquakes and the right side shows two thrust earthquakes.

# M7.0,r05,Average Horizontal

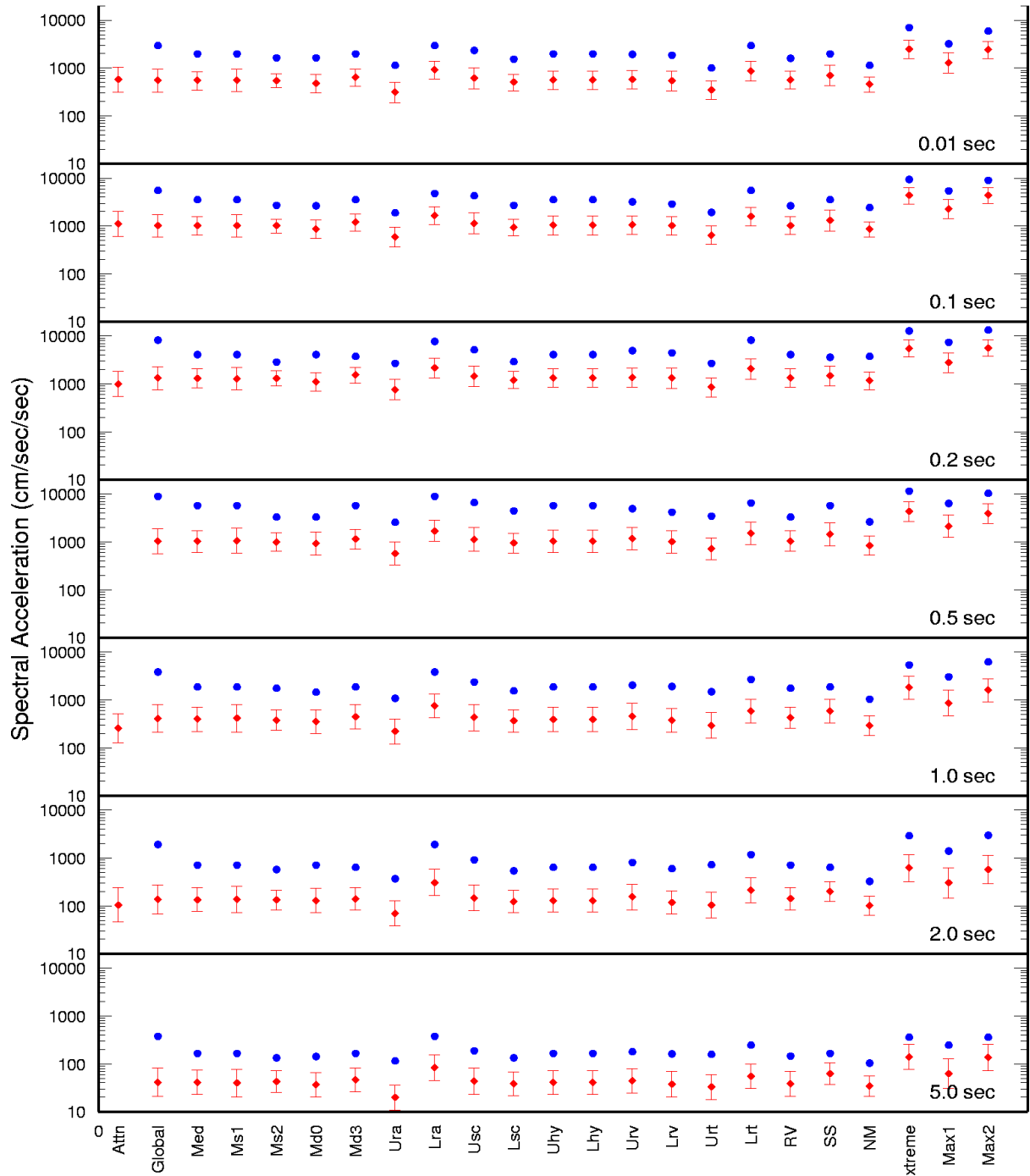


Figure 4a. Variation of the average ground motion response at a fault distance of 5 km as a function of period calculated for M7.0 scenario earthquakes indicated at the bottom of the figure. The median +/- one standard deviation, and maximum simulated ground motion levels are shown. For detailed explanation see text