Schweizerischer Erdbebendienst
Swiss Seismological Service

New Ground Motion Prediction Equations Spanning Weak and Strong Motion Levels

Paper No: S51A-0230

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I. Abstract

We present a new set of ground motion prediction equations for horizontal peak ground acceleration (PGA), peak ground velocity (PGV), and peak displacement (PGD, high-pass filtered at 3 sec) derived from ground motion records up to 200 km away from earthquakes over the magnitude range 2 < M < 8 for PGA and PGV, and the magnitude range 2 < M < 7.3 for PGD. We adopt a functional form used by Cua (2005) and Cua and Heaton (2008) that allows for a linear dependence of the log of peak ground motion on magnitude for events with M < 5, and magnitude/distance dependent saturation for events with M > 5. We fit this functional form to a dataset of observed PGA and PGV from 1) a predominantly weak-motion southern California dataset, and 2) the Boore and Atkinson (2006) subset of the Next Generation Attenuation (NGA) project strong motion dataset (www.peer.berkeley,edu/products/nga_project.html). At weak motion levels, the new equations are consistent with the small-amplitude equations (Quitoriano, 2003) used by the ShakeMap system for M < 5.3. The new equations also predict median PGA and PGV values consistent with the Boore and Atkinson (2006) and Campbell and Bozorgnia (2006) NGA equations, which are recommended for use above M 5, at the larger magnitude levels. There are discrepancies between the median ground motions predicted by the NGA relationships and our equations at the M=5 level, which is the lower bound of the applicable magnitude range of the NGA equations. These discrepancies may be indicative of a systematic bias towards higher ground motion levels at the lower magnitude bound of the NGA equations. Our findings suggest that in order to develop prediction equations that adequately characterize the median ground motion level at a particular magnitude (for instance, the lower magnitude bound of M=5 for the NGA equations), a sufficient quantity of data from lower magnitudes must be included. These results, based on southern California data and the NGA strong motion dataset, are in agreement with the findings of Bommer et al (in press) from a European and Middle Eastern strong motion dataset.

II. Methodology

We use the functional form of Cua (2005) and Cua and Heaton (2008), which is in turn, based on a functional form originallly proposed by Campbell (1997):

$$\log Y = aM + b(R_1 + C(M)) + d\log(R_1 + C(M)) + e \qquad (1)$$

where $R_1 = \sqrt{R^2 + 9}$

$$C(M) = c_1 \exp(c_2(M-5)) \times \quad \arctan(M-5) + \frac{\pi}{2}$$

In Equation (1), R1 is epicentral distance for M < 5, and the Joyner and Boore distance (closest distance to the surface projection of the fault) when available for M > 5. For M < 5, M is the magnitude reported by the Southern California Seismic Network (SCSN). SCSN local magnitudes have a 1-1 correspondence to moment magnitude Mw (Clinton et al, 2005). For observations from the NGA dataset, we use the listed Mw. Coefficients a, b, c1, c2, d, e are unknown, and are determined via a Neighborhood Algorithm (Sambridge, 1999) inversion. We solve for a separate set of coefficients for sites with Vs30 > 464 m/s (which we label as rock sites), and sites with Vs30 < 464 m/s (which are labeled as soil sites).

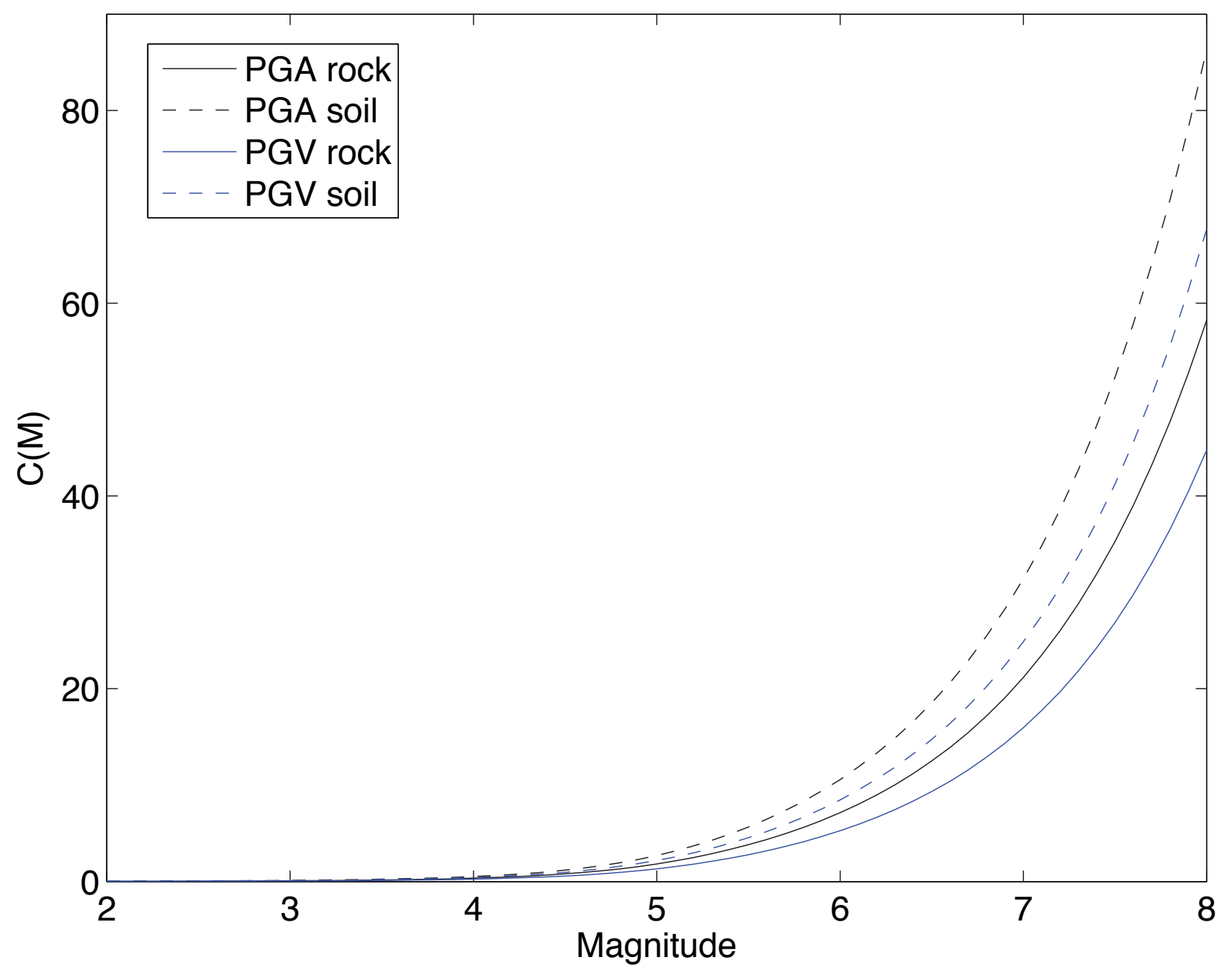


Figure 1: The saturation function C(M) as a function of magnitude for the different regressions (rock and soil PGA and PGV). C(M) allows saturation effects to come into play for M > 5 events by "increasing" the distance of a site from the source region. In general, soil ground motions exhibit stronger saturation effects than ground motions recorded on rock sites.

III. Dataset

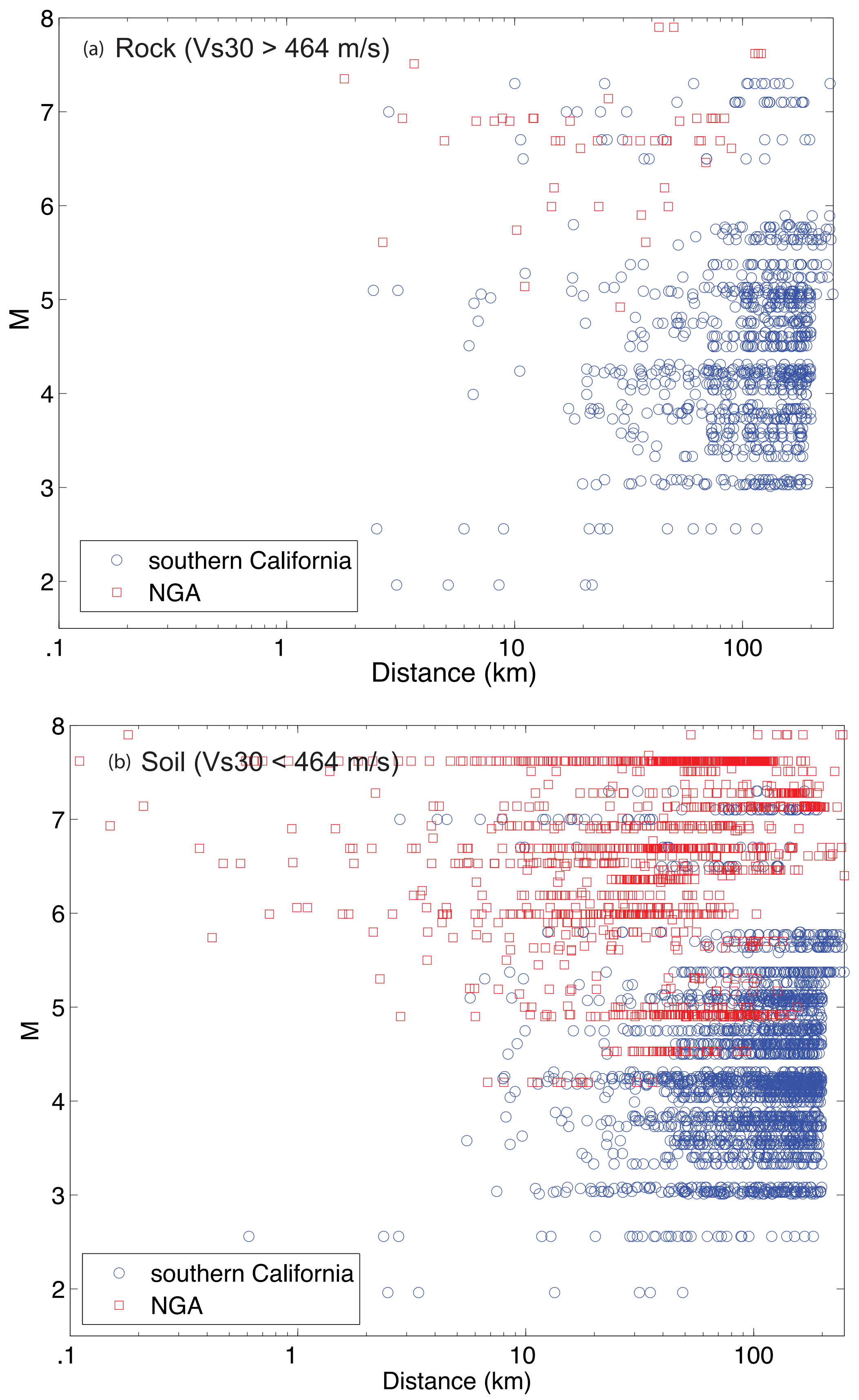


Figure 2: The distribution in magnitude and distance of PGA and PGV observations included in this study on (a) sites with Vs30 > 464 m/s (termed rock sites in this study), and (b) sites with Vs30 < 464 m/s (termed soil sites). Of the southern California data, 958 observations are from rock sites, and 2,630 from soil sites. We use the Boore and Atkinson (2007) subset of the NGA strong motion dataset. The Boore and Atkinson subset contributes 50 observations to the rock category, and 1,557 observations to the soil category. Henceforth, we refer to the Boore and Atkinson subset of the NGA dataset as the NGA dataset for brevity.

IV. Discussion

Our relationships capture the magnitude-dependence of distance attenuation (Figure 3). This characteristic of ground motion scaling is most evident when large magnitude ranges are considered. Our relationships are consistent with what would be expected if:

- small magnitude and large distance amplitudes (acceleration, velocity, and displacement) scale with seismic moment (Mo)

-large magnitude and small distance accelerations completely saturate (which means that high frequency radiated energy scales as rupture area, which is Brune's model without the stress drop term)

-large magnitude and small distance displacements scale as Mo^(1/3), or average slip

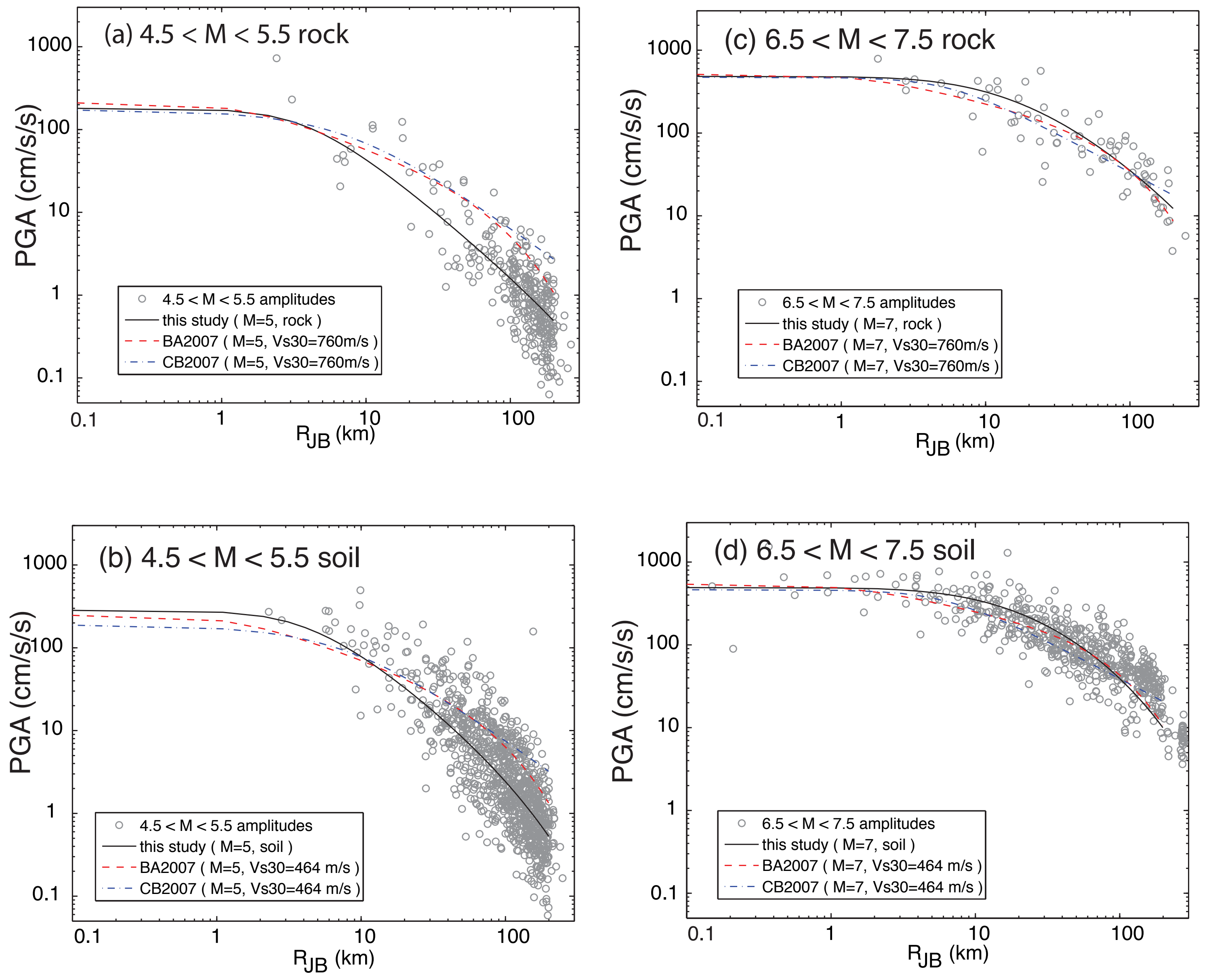
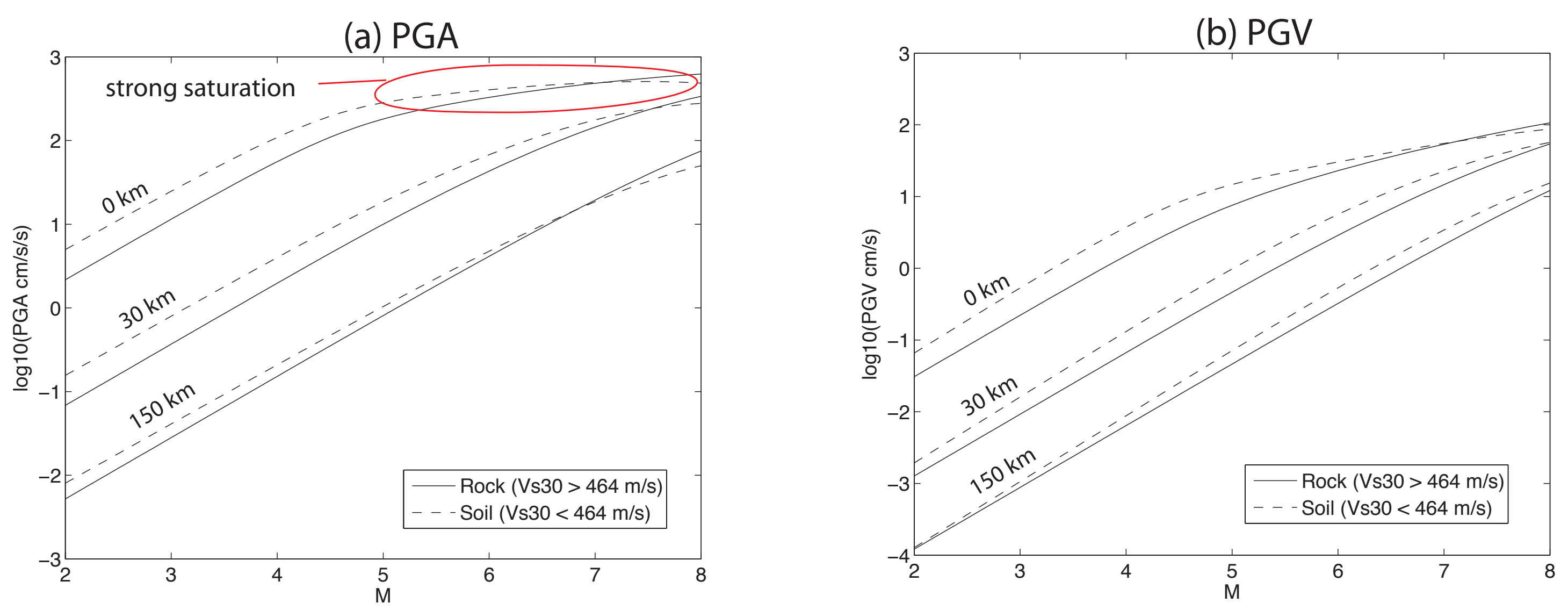
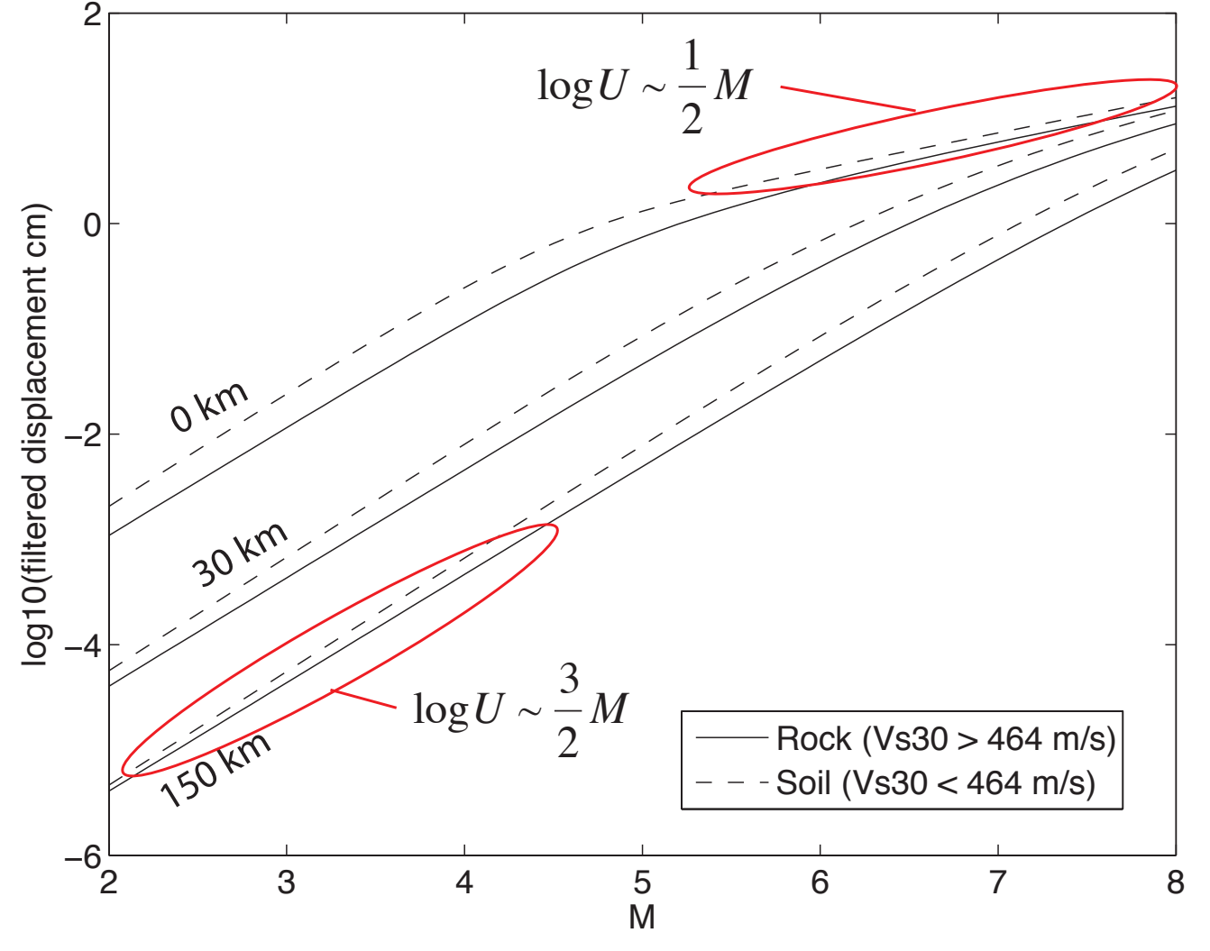


Figure 3: Observed PGA amplitudes from the combined southern California and NGA datasets for 4.5 < M < 5.5 recorded on (a) rock and (b) soil sites, along with the median M=5 PGA levels predicted by the relationships in this study, Boore and Atkinson (2007), and Campbell and Bozorgnia (2007). Subplots (c) and (d) show similar plots for data in the magnitude range 6.5 < M < 7.5, with the median M=7 PGA predicted by the same set of relationships. The NGA amplitudes are expressed in terms of GMIrot50, a measure of horizontal ground motion that is independent of sensor orientation (Boore et al, 2006). The southern California ground motion amplitudes (Figure (1)) are expressed in terms of the geometric mean of the as-recorded components. There is general agreement between our new equations and the NGA relationships at the upper magnitude levels (subplots c, d). However, the NGA relationships seem to overpredict the median PGA from the 4.5 < M < 5.5 observations. PGV exhibits similar behavior.



(c) high pass filtered displacement



Note: Oversaturation of soil amplitudes at close distances to large events is evident in subplots (a) and (b). This is indicative of nonlinear site amplification.

Figure 4: Saturation effects are strongest for PGA, and decrease with decreasing frequency. The total saturation of near-source PGA for large magnitudes is consistent with near-source high frequency ground motions being incoherent noise, independent of magnitude and total slip. This implies that high frequency radiated energy scales with rupture area, which is the Brune spectral model without the dependence on stress drop. Scaling relations lead us to anticipate the following assymptotic behavior for any ground motion prediction equations: 1) when the distance is large compared to source dimension, low frequency ground motions (displacement U) scale with seismic moment:

$$\log U_{far\&lowfreq} \sim \log M_O \sim \frac{3}{2} M$$

2) for near-source, low frequency ground motions, we expect peak displacements to scale with size of slip on the nearby fault segment, or

$$\log U_{near\&lowfreq} \sim \log \bar{D} \sim \log M_o^{1/3} \sim \frac{1}{2} M$$

The displacement scaling in subplot (c) is consistent with these expectations.

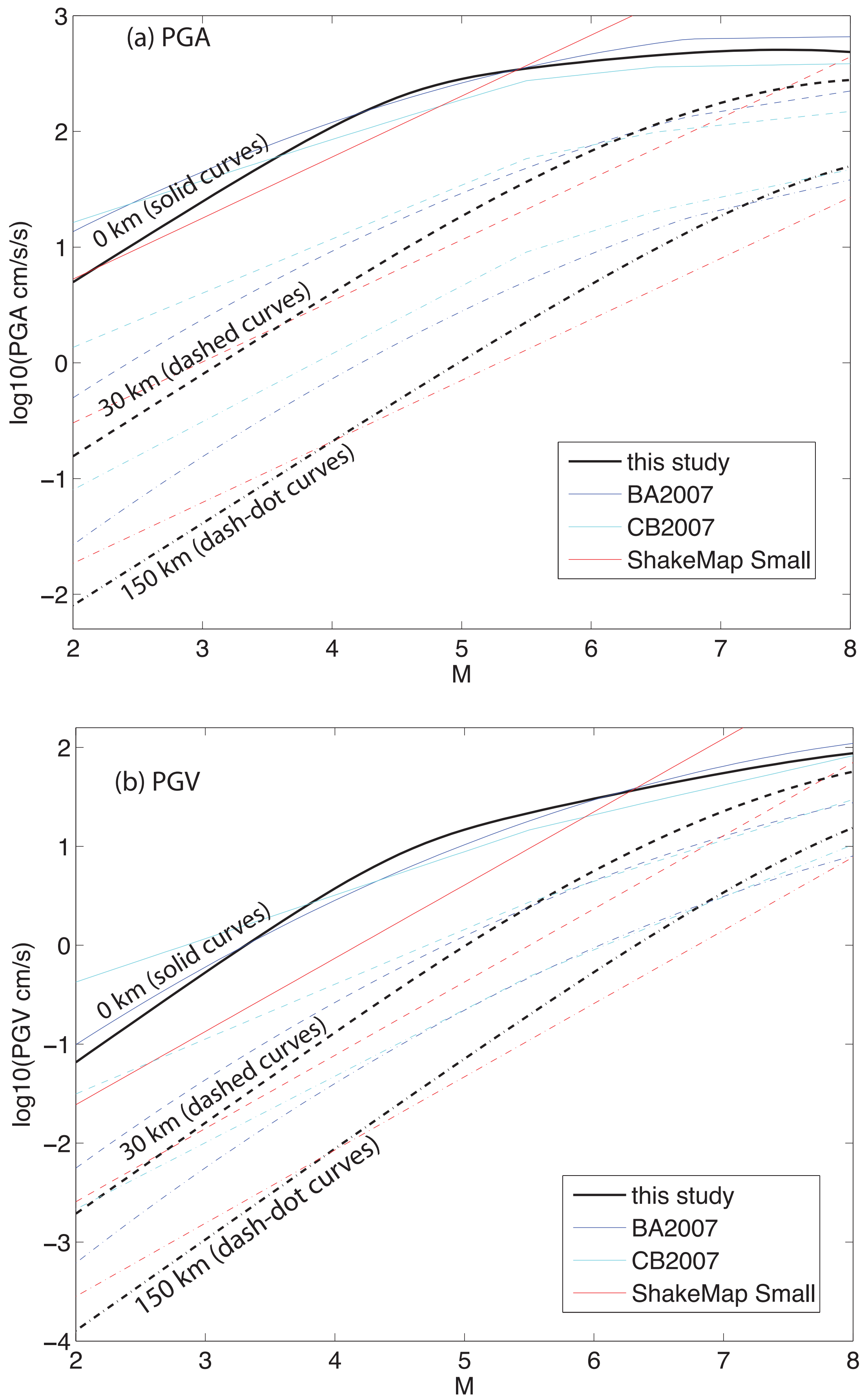


Figure 5: Scaling of (a) PGA and (b) PGV amplitudes as a function of magnitude at various distances from this study, Boore and Atkinson (BA2007), Campbell and Bozorgnia (CB2007) and the ShakeMap Small amplitude relationships (Quitoriano, et al 2003). (The ShakeMap Small amplitude regression relationship, which is a Perl module in the USGS ShakeMap distribution, is used by many ShakeMap operations for M < 5.) Our PGA and PGV levels are consistent with BA2007 and CB2007 and at the larger magnitudes (M > 5). However, both NGA relationships (BA2007, CB2007) tend to overestimate ground motion amplitudes for M < 5. The ShakeMap Small amplitude relationships overestimate ground motions for M > 5. The scaling relationships implied by the Boore and Atkinson (2007) and ShakeMap regressions cannot be extended beyond the magnitude ranges from which they are derived.

IV. Conclusions

We develop new equations for PGA, PGV, and high pass filtered displacement that are derived from data in the magnitude range 2 < M < 8. These relationships can be used in earthquake early warning, or ShakeMap-type applications, which, while most relevant for large, damaging (but infrequent) earthquakes, must be tested, validated, and calibrated on smaller, more frequently occurring events. We compare the median PGA and PGV levels predicted by our new equations with the Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) NGA relationships, as well as the ShakeMap Small amplitude equations. Our relationships span the combined magnitude range of the NGA and ShakeMap equations. Using an extended magnitude range (2 < M < 8) allows our ground motion prediction equations to capture scaling characteristics that are consistent with earthquake source physics. These characterisitcs are not evident when considering more limited magnitude ranges.