The Use of Empirical Data, Numerical Simulation and Expert Judgment to Define Upper Bounds on Ground Motions: Insights from the PEGASOS Project

Julian J. Bommer
Dept. of Civil & Environmental Engineering, Imperial College London, SW7 2BU, UK

Introduction

This document briefly summarizes the methodological approaches to defining upper bounds on earthquake ground motions in rock employed in the PEGASOS Project (Abrahamson *et al.*, 2002).

Upper Bounds in the PEGASOS Project

The PEGASOS Project had the benefit of hindsight in coming after the Yucca Mountain seismic hazard assessment had been completed (Stepp *et al.*, 2001) and the participants were aware of the need to consider upper bounds on ground motions since the hazard was to be calculated to annual frequencies of exceedance as low as 10^{-7} (Abrahamson *et al.*, 2002).

The members of the expert panel for sub-project 2 (SP2) on ground-motion models had the benefit of knowing that the issue of upper bounds on ground motion was likely to arise, but the resources available to help constrain their estimates were limited. The experts were required to provide estimates of upper bounds on rock site spectral accelerations over a range of response frequencies as functions of magnitude and distance. A logic-tree approach was adopted with each expert assessing possible levels and assigning them relative weights.

The most important resource made available at the request of the panel of ground-motion experts was two sets of simulations performed by URS Corporation (Arben Pitarka and Paul Somerville) and OGS Trieste (Enrico Priolo and colleagues) to generate extreme ground motions for a few selected magnitude-distance pairs. The input to these models were reviewed by Professor Raúl Madariaga and only one set of simulations – using super-shear rupture velocities – was unambiguously judged to be unphysical and hence that set of results were disregarded by the experts.

Other resources at the disposal of the authors included the following: existing empirical ground-motion prediction equations; a large databank of strong-motion records; and previous studies proposing upper bounds on earthquake ground motions. The latter were mostly published more than 20 years ago (see review in Bommer *et al*., 2004) and although of historical interest these were generally not considered to be particularly useful resources for the solution of the problem.

Examination of the residuals in a number of strong-motion data sets reveals that the largest outliers are consistently at least at the 3σ level (Bommer *et al*., 2004). Defining the upper bounds in terms of a number (ε) of standard deviations rather than absolute values of spectral acceleration was not the favored approach in the PEGASOS project for two simple reasons: (1) the bounds, if they exist, are physical rather than statistical measures, and (2) if the bounds were defined in terms of ε, then in a logic-tree formulation this would create the illogical result of different absolute values for each ground-motion prediction equation.

In the PEGASOS project, a third expert panel – in addition to those on seismic sources and on ground motions – was established for site response, and they were also charged with defining upper limits on ground motions as imposed by the finite strength of near-surface materials (e.g. Pecker, 2003, 2004). However, since this issue is not relevant to the Yucca Mountain project, it is not discussed in the presentations.

Expert Estimates of Upper Bounds

The five ground-motion experts in SP2 were charged with providing estimates of upper bounds on spectral accelerations in hard rock sites at various response frequencies for a range of distances (up to 100 km) and for magnitudes from M_w 5.5 to M_w 7.5. The approaches adopted by the experts varied but in each case the experts produced a range of estimates, reflecting the large epistemic uncertainty in the upper bounds, and weighting these accordingly.

Expert 1 used five different criteria, each weighted according to his confidence in their reliability: the two sets of numerical simulations, the largest amplitudes in the empirical dataset multiplied by a factor of 1.5, and the 2.5σ and 3.0σ levels from a particular ground-motion prediction equation; the highest weighting was given to the URS “Max1” simulations. These options and weights were then used to infer mean, minimum and maximum estimates of upper bounds. Experts 2 and 3 used similar criteria, but without a formal weighting scheme, using the empirical data without adjustment, and considering much higher exceedances from existing empirical equations (up to +4σ). Experts 1, 2 and 3 all used a similar format to express their estimates of the upper bounds: adding certain numbers (not necessarily integers) of standard deviations to the median estimates from a particular attenuation equation – either Ambraseys *et al.* (1996) or Abrahamson & Silva (1997). It is important to emphasize that these numbers were not assigned any particular statistical significance: this was simply a tool of convenience, equivalent to changing the constant term in the equations, to obtain estimates of the upper bounds over a range of magnitudes and distances.

Expert 4 used a different approach, starting with an anchor point, inferred from the simulations and the empirical data, of PGA equal to 3.0*g* for an M_w 7 earthquake at 1 km. The response spectral shape and the scaling of all ordinates with magnitude and distance were obtained directly from the equations for central and eastern US by Somerville *et al*. (2001). This provided the best estimates: upper and lower estimates of the upper bounds were then obtained by multiplying these values by 2.0 and 0.5.

Expert 5 used another approach, with estimates based primarily on the simulations with sub-shear rupture velocities. The bounding values were interpolated for various magnitudes and distances using the stochastic model of Bay (2002) for Switzerland, with values of the stress parameter $\Delta\sigma$ high enough to match the estimates from the numerical simulations. Estimates of the upper bounds were found using values of 150, 200 and 250 bars for $\Delta\sigma$.

Figure 1 compares estimates of upper bounds on PGA for a particular scenario from the five experts, with the relative weighting assigned by the expert to each estimate. The difference between the lowest and highest estimates is almost one order of magnitude. It can also be observed that in some cases the ranges of estimates proposed by different experts were mutually exclusive. Recalling the objective of a SSHAC Level 4 seismic hazard assessment (Budnitz *et al*., 1997) to produce estimates that "*must be the composite distribution of views represented in the appropriate scientific community*", it is reasonable to conclude that the estimates of upper bounds have effectively captured "*the centre, the body, and the range of technical interpretations that larger informed technical community would have if they were to conduct the study*". The wide range of the estimates is simply a reflection of the large epistemic uncertainty associated with these estimates, for which there is currently little empirical or theoretical evidence. If one accepts the principle that estimates should encompass the space within which future estimates, based on increased data and improved knowledge, will fall, then it is likely that the SP2 experts in PEGASOS achieved this aim.

The SP2 experts were also required, as mentioned earlier, to provide estimates on the upper bounds for vertical ground motions. In the PEGASOS project, models for vertical ground motions were not provided independently but rather experts were required to provide models for the ratio of vertical-to-horizontal (V/H) motions. Experts 1 and 5 estimated the upper bounds on vertical ground motions by multiplying their estimates for upper bounds on horizontal motions by the median V/H ratios. Expert 4 provided his estimate as the horizontal upper bounds multiplied by ⅔. Expert 3 estimated the vertical upper bounds in the same way as for the horizontal motion, using the URS simulations and the vertical components of the empirical data. Expert 2 assumed that the upper bounds on the vertical motion would be equal to those on the horizontal motion.

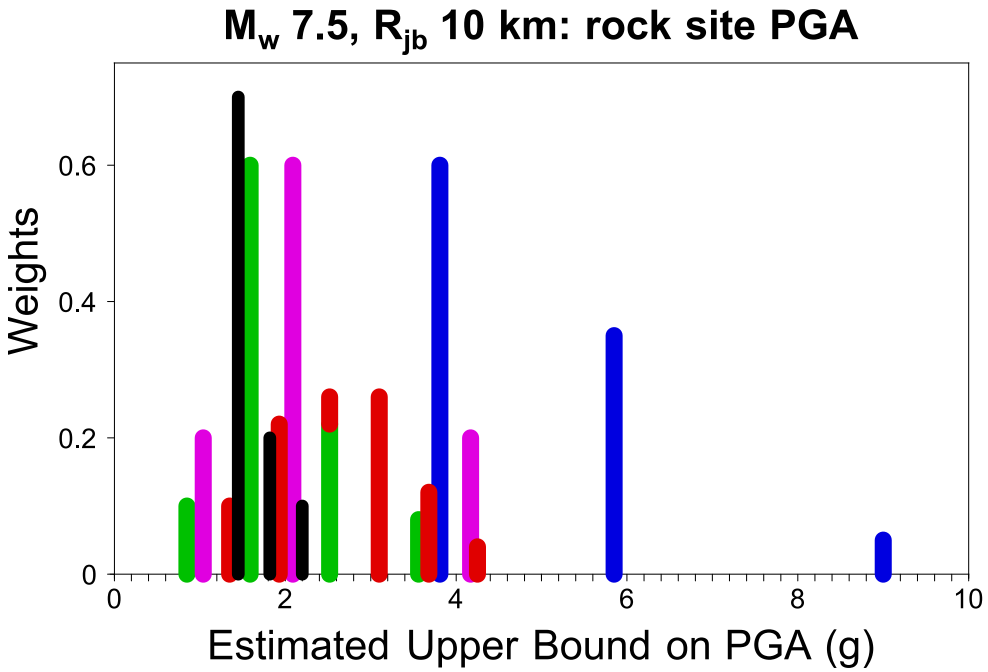

Figure 1. Estimated upper bounds on horizontal peak ground acceleration for a specific earthquake scenario, with associated weights, proposed by the five SP2 experts.

Conclusions

The issue of upper bounds on earthquake ground motions was addressed in the PEGASOS project because of the very low annual frequencies of exceedance considered for the PSHA and also because of the experience of the Yucca Mountain project.

- The general view of the experts charged with estimating upper bounds on rock motions was that the empirical data is not sufficient to provide reliable indications of the upper tails of the distribution of residuals in ground-motion prediction equations and at best can indicate lower bounds on the upper bounds.
- The most promising generic tool for obtaining reliable estimates for upper bounds is numerical simulations but the key factor will be defining the extreme but physically realizable combinations of source parameters (stress drop, rise time, rupture velocity, etc.) for the simulations, which can probably only be determined using dynamic models.
- Although the view of the SP2 experts in PEGASOS was that the upper bounds should be defined physically rather than statistically, it may only prove possible in

the short- or medium-term to define the joint probability distributions of earthquake source parameters and then to obtain probabilistic estimates of extreme motions.

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