Liquefaction Intensity Measure

Steve Kramer and Bob Mitchell
University of Washington

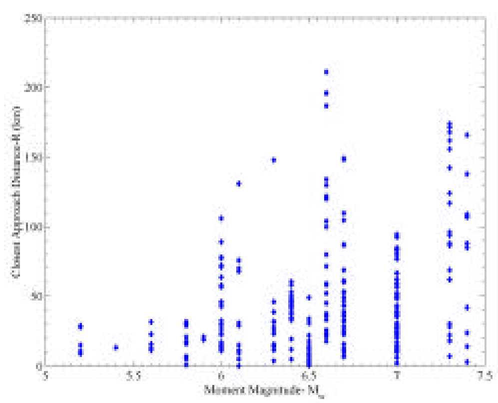
We propose the use of a new intensity measure (IM) for soil liquefaction with the expectation that it will be combined with one or more structural IMs to form a vector IM that will be useful for predicting the performance of soil-structure systems that include liquefiable soils. The IM, which we refer to as CAV_5, is a variant of cumulative absolute velocity defined as

$$CAV_5 = \int_0^{\infty} \langle c \rangle |a(t)| dt \qquad \text{where} \qquad \langle c \rangle = \begin{cases} 0 & |a(t)| < 5\, cm/\sec^2 \\ 1 & |a(t)| \geq 5\, cm/\sec^2 \end{cases}$$

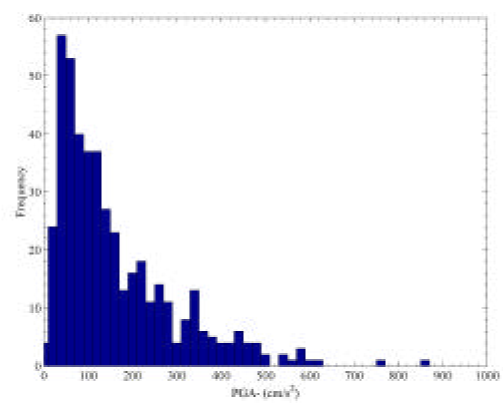
In this definition, 5 cm/sec^2 represents a threshold acceleration below which there is no contribution to CAV_5.

Background

This IM was identified by performing nonlinear, effective stress-based, one-dimensional site response analyses on nine profiles (three liquefiable layer thicknesses and three liquefiable layer densities) subjected to 455 input motions taken from a ground motion database provided by Dr. C.B Crouse. The database consisted of 455 records (227 two-component records and one 1 component record) spanning a range of magnitudes and distances (including near-field motions) recorded at rock or very dense soil/soft rock sites within deep basin sites during 22 California strike-slip or reverse-slip earthquakes. The range of magnitudes and distances, and the distribution of PHA, within the database are shown below.



Magnitudes and distances for ground motions used to identify liquefaction IM



Distribution of PHA values for motions used to identify liquefaction IM

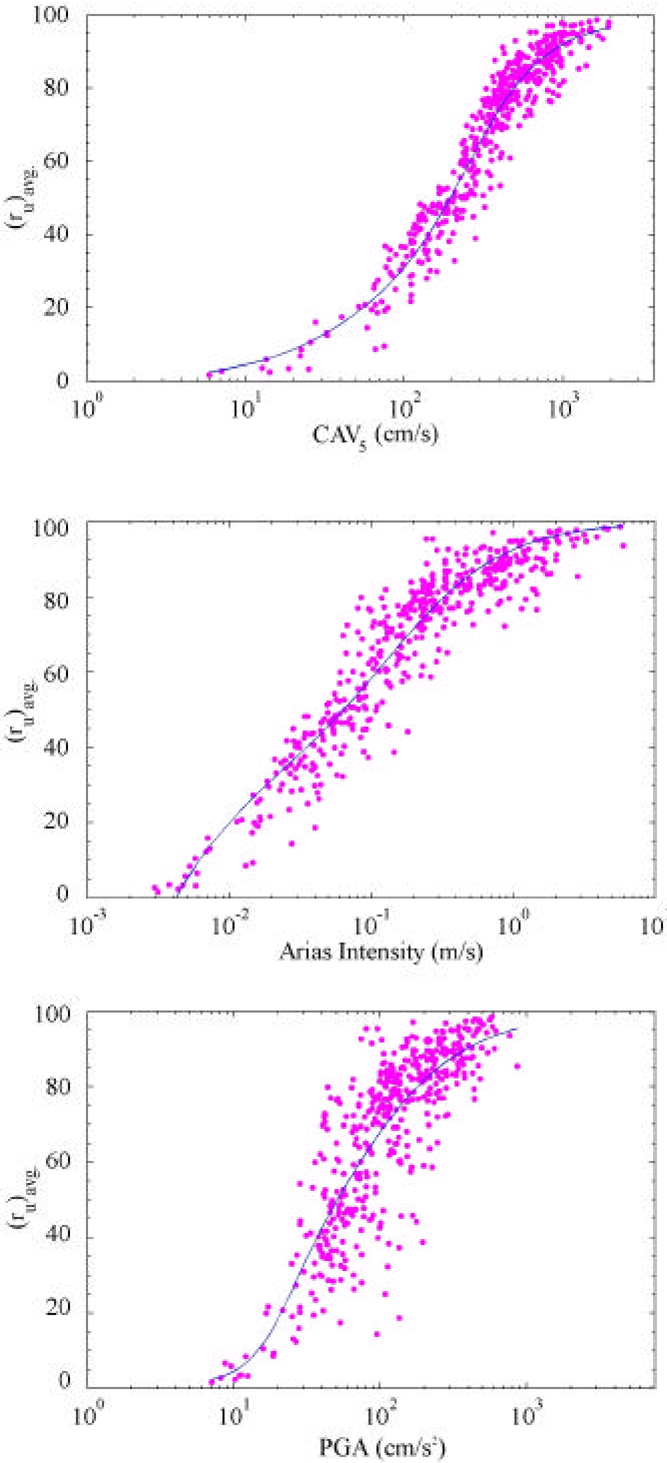
The site response analyses were performed using a program, WAVE, developed at the University of Washington. This one-dimensional, explicit finite difference code uses the UWsand constitutive model, a model that has been shown to produce pore pressures that are consistent with observations of field behavior of liquefiable soils.

For each site response analysis, the mean (depth-averaged) value of pore pressure ratio (r_u, a value that goes linearly from 0 to 1 as the effective stress goes from its initial value to zero) was computed at the end of shaking. Pore pressure redistribution during shaking was not considered. The computed mean pore pressure ratios were plotted against each of over 350 candidate IMs. A short-list of the IMs that showed the best correlation (highest efficiency) was developed for further study. Two additional parameters, PHA and Arias intensity, were carried through for historical reasons – both have been used for liquefaction analysis in practice (PHA has been the dominant IM for liquefaction analysis for many years; Arias intensity was proposed as an alternative a few years ago). The short-listed parameters were examined from the standpoints of efficiency and sufficiency (to use Allin Cornell's terms), and also from the standpoint of simplicity. This process led to the selection of CAV_5 as an improved IM for liquefaction analysis.

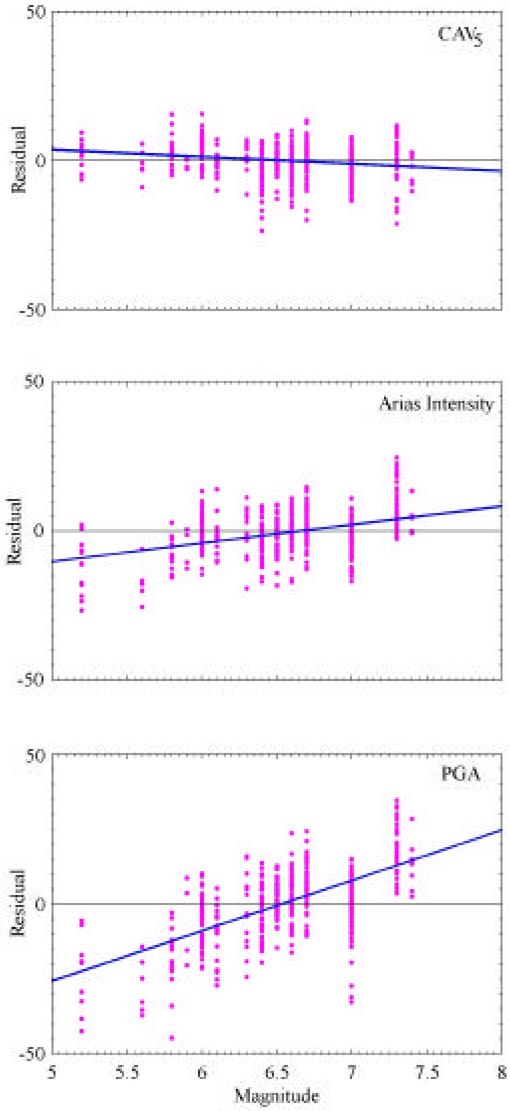
Justification

The following pages show a series of plots that illustrate the efficiency and sufficiency of CAV_5, along with similar plots for the historically-used liquefaction IMs, PHA and Arias intensity. The plots are for the intermediate thickness and highest density considered (selected to avoid showing data for which most profiles liquefied with $r_u = 1.0$), but they are consistent with the results obtained for other thicknesses and densities. The efficiency plots show much smaller dispersion in the relationship between CAV_5 and mean pore pressure ratio than do the historical parameters. The sufficiency plots show a significantly lower dependence of average pore pressure ratio on magnitude and distance when correlated to CAV_5 than to either of the historical parameters. The inadequacy of PHA as a sole descriptor of intensity for liquefaction problems has long been recognized, and accounted for by the use of magnitude scaling factors. It is possible to develop a "magnitude-weighted PHA" that shows good sufficiency (w/r/t *M*), but its efficiency is still relatively low.

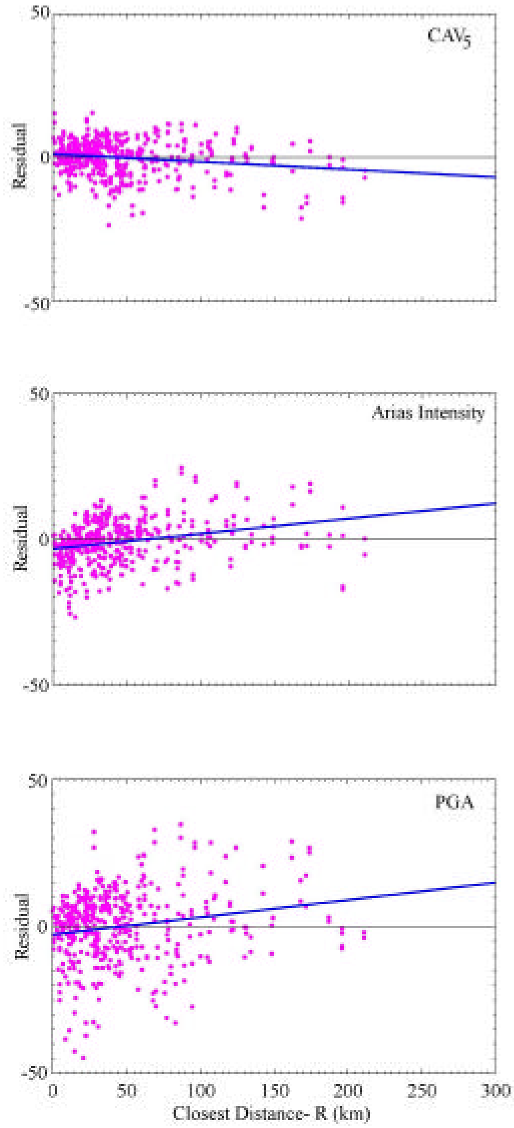
CAV_5 is an easy parameter to compute, and we believe its efficiency and sufficiency is significantly better than that of the historical liquefaction IMs. We hope that it will be considered for inclusion in vector IMs that apply to structures founded on liquefiable soils.



Variation of mean pore pressure ratio with various IMs for typical liquefiable soil profile. Decreasing dispersion of $(r_u)_{avg}$ values about the best fit (blue) line denotes increasing efficiency of the IM. Normalized residual sum of squares for the three IMs are 1.00, 1.51, and 4.08 for CAV_5, Arias intensity, and PHA, respectively.



Dependence of residuals on magnitude. Blue line represents linear regression on residuals



Dependence of residuals on distance. Blue line represents linear regression on residuals

Linear least squares fits to residuals plots. Coefficients of M and R terms indicate relative sufficiencies of the various IMs. Lower coefficients (i.e. flatter slopes) indicate higher sufficiency.

IM	Magnitude	Distance (km)	Residual Sum of Squares
CAV_5	-2.38M + 15.4	-0.027R + 1.18	18,093
Arias Intensity	6.19M - 41.2	0.052R - 3.21	27,285
PHA	16.78M - 109.6	0.059R - 2.79	73,897