THE SAM PROCEDURE FOR SITE-ACCELERATION-MAGNITUDE RELATIONSHIPS

by

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SYNOPSIS

Early work on the relationships of site characteristics, horizontal peak accelerations, magnitude, attenuation with distance, and probabilistic variations is extended with more data, refined, and simplified. New estimation procedures called SAM IV and SAM V are provided to supersede previous SAM versions. The data used include all California and western Nevada strong motion records from 1933 through 1970 and, for studies of rock and alluvium motion, statistics from 2,713 records of ground motion induced by underground nuclear explosions. Comparisons to studies and estimation procedures by others are provided.

GLOSSARY OF TERMS

a = peak ground acceleration, gal

a_y = peak ground acceleration associated with probability level y, gal

b_1, b_2, b_3 = constants determined from the data

$\overline{b}$ = the Blume site factor per Equation (4)

G = the standard geometric deviation

ln = natural logarithm, base e

M = Richter magnitude, as given in United States Earthquakes

R = hypocentral distance, km

SAM = acronym for Site-Acceleration-Magnitude

V_s = site shear velocity, ft/sec

ρ = site specific density, dimensionless

y = standard normal variable with zero mean and unit standard deviation

INTRODUCTION

In an earlier paper (1), I outlined a procedure for estimating the relationships of site materials, horizontal peak acceleration, magnitude, and epicentral distance, which came to be known as SAM, for Site-Acceleration-Magnitude. Subsequently, the procedure was improved to include its probabilistic aspects on a more formal basis; this became SAM II. Another version, which included more data, became SAM III. Neither SAM II or III were published except in report form. In recent years others have published papers comparing the results of different studies and data sets. Some of these comparisons have been based on soil characteristics improper for SAM comparisons, and in one case the SAM equation was reprinted incorrectly. In view of this and the availability of more recorded ground motion data from both earthquakes and underground nuclear explosions, new

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procedures called SAM IV and SAM V, have been developed, superseding the earlier SAM, SAM II, and SAM III. SAM IV applies to earthquake magnitudes of 6½ or less and SAM V to magnitudes greater than 6½. The SAM procedures continue to be unique in that they consider, in simple form, magnitude, epicentral distance, focal depth, site characteristics, peak acceleration, and probabilistic variations.

THE DATA

The natural earthquake data used are from United States Earthquakes (2), which provides the official record of corrected peak acceleration, magnitude, and epicentral distance. All data from 1933 through 1970 for California and western Nevada were used. This excludes data from the 1971 San Fernando earthquake, which were not published at the time of the study. Furthermore, it seemed desirable not to include the bias that might result from so much data from one earthquake, especially from a somewhat non-typical thrust fault motion. The focal depth is not provided in United States Earthquakes, and yet it was desired to use hypocentral rather than epicentral distance. SAM IV and V involve the considered assumption that the average focal depth is 8 km.

A statistical study such as this should include all appropriate data. Using only the greater of the two horizontal motions does not seem logical or representative of design conditions and tends to bias the data. In this study, both horizontal values were used when available in United States Earthquakes. Some investigators have used all data available at the time of their study; some have arbitrarily cut off at some level such as 1 gal, 5 gal, or more; and some have used a combination of cutoff levels. Of course, the instrument used to record the motion is in itself a cutoff. The effects of cutoff were studied.

Altogether, 795 horizontal strong motion record-components from natural earthquakes were used. In addition, for consideration of the relative motion on rock and alluvium at various distances, results from the statistical analysis of 2,713 ground motion records from nuclear seismology were included (3).

TREATMENT OF THE DATA WITHOUT SITE ADJUSTMENT

After considerable study, the form of equation selected (4) was

$$a = b_1 e^{b_2 M} (R + 25)^{-b_3} \qquad (1)$$

Taking the natural logarithm of Equation (1) results in Equation (2):

$$\ln a = \ln b_1 + b_2 M - b_3 \ln(R + 25) \qquad (2)$$

There are two independent variables, M and ln(R + 25), and one dependent variable, ln a. Multiple linear regression analysis (5) was performed with various data sets to obtain the mean value of the three variables, the three constants, and the standard deviation (ln G). At this stage no distinction was made for site conditions. Table I provides data for several runs. The expression for the acceleration at any probability level, y, in lognormal form is

$$a_y = e^{\ln b_1 + b_2 M} (R + 25)^{-b_3} G^y \qquad (3)$$

The results for runs 51 and 52 are almost the same, indicating very few data points below 1 gal. The cutoff levels for acceleration in runs 52, 53, and 54 affect ln G significantly. It was decided to use all data (run 51) for developing SAM IV for M values not exceeding 6.5. It can be seen by comparing runs 51 and 71 that there is little difference whether all data (run 51) are used or only data equal to or less than 6.5M (run 71) are used. There is less dispersion in the major earthquake data. It was decided after study that the data set of run 56 provided the optimum combination of M cutoff level and the number of sample points for major earthquakes, and it was used as the basis of SAM V for M > 6.5.

SAM IV AND SAM V

The original SAM procedure included adjustments for site characteristics based on data from the work of Gutenberg and Richter (6). New data show that the relative peak motion on rock versus alluvium is strongly dependent on epicentral distance. Although there is still a sparsity of data for rock stations under earthquake motion, there is considerable information from both rock and alluvium stations under motion from underground nuclear explosions. Figure 1 shows the ratio of peak acceleration in alluvium to that on rock plotted against hypocentral distance. This plot is based on a statistical study of 1,911 records on alluvium and 802 on rock (3). Most of the records were taken in Nevada as part of the seismic effects monitoring program associated with underground nuclear detonations at the Nevada Test Site. The findings are consistent with the more limited data from natural earthquake records. It was assumed that rock motion and alluvial motion are equal at 4 km hypocentral distance (see Figure 1), and also that the site impedance, taken as the product ρV_S, as in the original SAM procedure (1), is the best single measure of site conditions. Consideration of station conditions where earthquake strong motion has been recorded in California and western Nevada led to the assumption that the average ρV_S for the 1933-1970 data analyzed in Table I can be taken as 2,000 fps. Adjustments are to be made for other site conditions.

The original Blume site factor, $\overline{b}$, was determined from plots (1). It has since been found that Equation (4) gives equally useful results.

$$\overline{b} = \frac{1}{2} \log_{10} (\rho V_S) \qquad (4)$$

With Equation (4), $\overline{b}$ for 2,000 fps is 1.65, which is applicable to the data in Table I. Exponent b_3 in Equation (3) is replaced by $x\overline{b}$, where $x = b_3/\overline{b}$. Moreover, Equation (3) will be normalized so that, at R = 4 km, the peak acceleration will be the same for all values of $\overline{b}$ and motion will be as provided by the data from run 51 for SAM IV and run 56 for SAM V, all at constant values of y. The relative attenuation of ρV_S = 2,000 material to ρV_S = 12,000 material will be generally in accordance with Figure 1. Thus

<u>SAM IV (for M $\leq 6\frac{1}{2}$):</u>

$$a_y = 0.318e^{1.03M}(29)^{1.14\overline{b}}(R + 25)^{-1.14\overline{b}}(2.53)^y \qquad (5)$$

<u>SAM V (for M > $6\frac{1}{2}$):</u>

$$a_y = 26.0e^{0.432M}(29)^{1.22\overline{b}}(R + 25)^{-1.22\overline{b}}(1.81)^y \qquad (6)$$

The value of y selected is to be associated with the corresponding probability of exceedance from standard tables. When y = 0 the median acceleration is obtained. The value of a_y is the estimated peak acceleration that would be recorded by an instrument. It is not intended to be used directly in design or as a seismic coefficient without adjustment for other considerations (7). The equations are for California and western Nevada data, which may not be a good model for other locations.

COMPARISONS

Comparisons of attenuation curves and relationships of site characteristics, acceleration, and magnitude are difficult because of the complexity of the problem and the fact that investigators have used different data sets, parameters, cutoff levels, assumptions, and analyses. Comparisons will be made here by superimposing SAM curves on three plots by others.

Figure 2 is a plot by Donovan (8), in which the original SAM data (1) were plotted erroneously and/or hard rock ρV_s values were used erroneously in comparison to data generally for soft materials. The bottom curve should be replaced by the heavy curve, which is SAM (1) for ρV_s = 2,000 fps, a better basis for comparison. A SAM IV curve, not shown, would be better.

Figure 3 is a set of curves by Trifunac and Brady (9). SAM IV curves for M = 6.5 and ρV_s = 3,000 fps are superimposed for y = 0, 1, and 2. The y = 0 curve coincides with that shown for Esteva (4). If ρV_s were a smaller value, such as 2,000 fps, the accelerations would be greater at long distance:

Figure 4 from Page et al (10) shows acceleration points for three levels of magnitude. Curves are superimposed for M = 7 by the SAM V equation with ρV_s = 2,000 fps. Magnitude 7 is an average value for the data points from 6.0 to 7.9. Disregarding the 5.0 to 5.9 points, there is good correlation of the M = 7 curves and the 6.0 to 7.9 data points.

Trifunac (17) plotted curves (not shown) for peak acceleration for three magnitudes, three site classifications, and 0.9 confidence level. SAM V was used to plot comparison curves for his 8.5M and 5.5M earthquakes with the same confidence levels, using ρV_s = 2,000 fps for soft soil and 12,000 fps for hard soil. There was good general correlation for 8.5M except that SAM V provided somewhat lower values at short distances and somewhat greater values for soft soil at long distances. SAM V also provided more vari tion between soft and hard soil at long distances and less at short distances. SAM IV was used for 5.5M with generally good comparisons beyond 20 or 30 kilometers and lower values at shorter distances.

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TABLE I - DATA FROM MULTIPLE REGRESSION ANALYSES*

Run	M	Mean value of M	Mean of ln a (gal)	Mean of ln(R+25) (km)	ln b_1	b_2	b_3	ln G
51	All	5.324	2.330	4.435	5.195	1.030	1.883	0.930
52	All	5.326	2.339	4.434	5.211	1.020	1.873	0.923
53	All	5.311	2.897	4.291	5.044	0.805	1.497	0.770
54	All	5.324	3.330	4.182	5.265	0.691	1.343	0.727
70	$\geq$ 5-1/2	6.189	2.292	4.926	5.913	1.045	2.049	0.801
55	$\geq$ 6	6.548	2.269	5.149	7.464	0.900	2.154	0.768
56	$\geq$ 6-1/2	6.871	2.655	5.142	10.026	0.432	2.010	0.592
57	$\geq$ 6-3/4	7.363	2.494	5.334	9.883	0.516	2.097	0.372
66	$\geq$ 6	6.531	3.176	4.742	7.934	0.815	2.125	0.742
67	$\geq$ 6-1/2	6.843	3.553	4.718	9.519	0.412	1.862	0.677
68	$\geq$ 6-3/4	7.231	3.300	4.928	10.408	0.469	2.130	0.275
71	$\leq$ 6-1/2	5.127	2.288	4.344	5.123	1.034	1.873	0.959
72	> 6-1/2	7.200	2.877	5.086	8.940	0.659	2.125	0.470

*All United States Earthquakes data (1933 through 1970) were used except in runs 66, 67 and 68, for which distances > 150 km were deleted; in runs 52, 53, and 54 accelerations were cut off at 1, 5, and 10 gal, respectively.

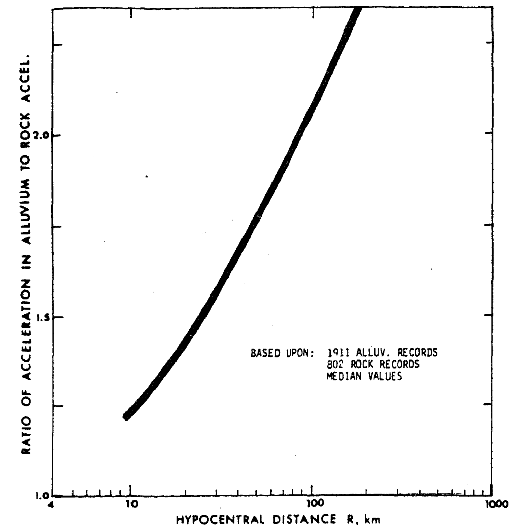

FIG. 1--ACCELERATION RATIOS FOR NUCLEAR EXPLOSIONS

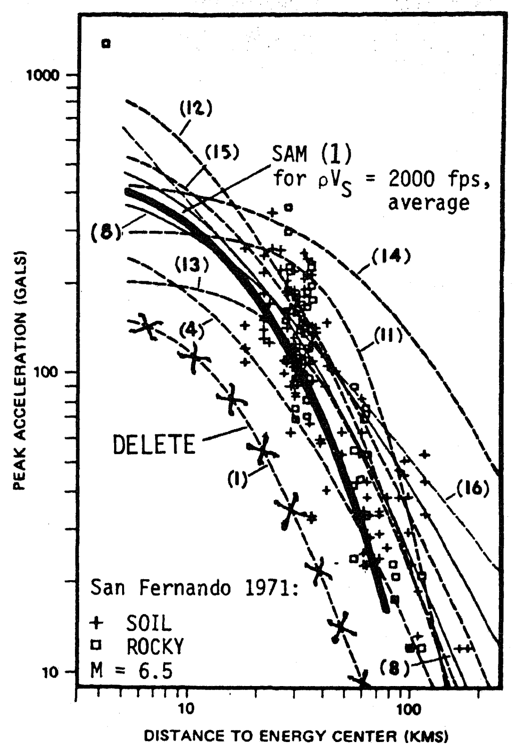

FIG 2--COMPARISON OF ORIGINAL SAM TO REFERENCE 8 DATA

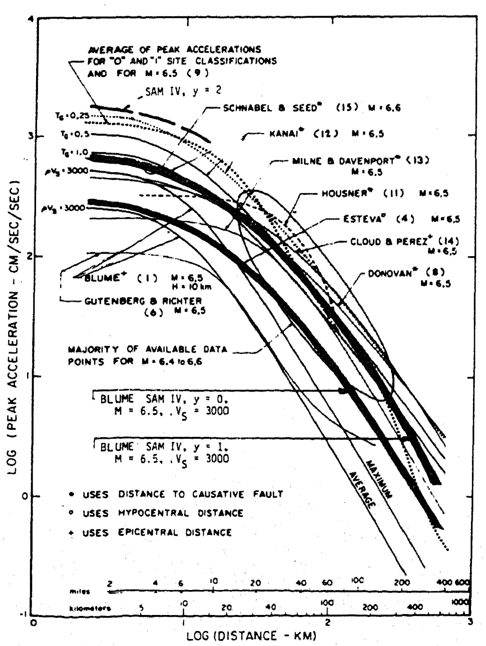

FIG 3--COMPARISON OF SAM IV TO REFERENCE 9 DATA

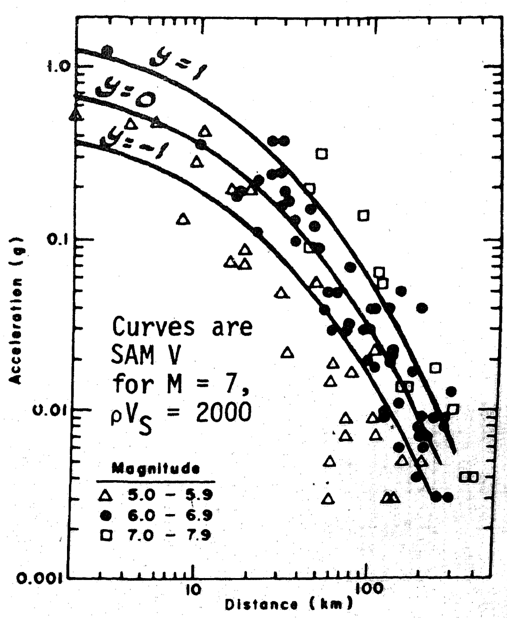

FIG 4--COMPARISON OF SAM V TO REFERENCE 10 DATA

DISCUSSION

V. Bune (USSR)

We know magnitudes M_s, M_b, M_l. What type of magnitudes you used ?

J.L. Justo (Spain)

The discussor tried to apply Esteva's method some years ago, and found that in this way, the distribution is not of a normal (Gaussian) type, because there is a concentration of data near low values of (R+25).

The discussor wondered whether you have considered that, in this case, the Gaussian formulas of statistics are not applicable.

Author's Closure

With regard to the question of Mr. Bune, we wish to state that the magnitudes used in the study are those listed in the various annual reports, "United States Earthquakes", published by the U.S. Department of Commerce.

The magnitudes were calculated from Richter's original magnitude scale for locally-recorded earthquakes in southern California and adjoining regions. Magnitudes determined this way are denoted M_L.

With regard to the question of Mr. Justo, we wish to state that the Gaussian distribution does not apply to problems of prossible extremes on one side and zero limits on the other, such as the absolute accelerations of earthquakes. We have not used Gaussian formulas in the "SAM" development, but rather the lognormal distribution (which is, of course, a Gaussian or normal treatment of the logarithms). We have found that the lognormal, the gamma, or the extreme distributions fit the data quite well.