ESTIMATION OF RESPONSE-SPECTRAL VALUES AS FUNCTIONS OF MAGNITUDE, DISTANCE, AND SITE CONDITIONS

By

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ABSTRACT

We have developed empirical predictive equations for the horizontal pseudo-velocity response at 5-percent damping for 12 different periods from 0.1 to 4.0 s. Using a multiple linear-regression method similar to the one we used previously for peak horizontal acceleration and velocity, we analyzed response spectra period by period for 64 records of 12 shallow earthquakes in western North America, including the recent Coyote Lake and Imperial Valley, California, earthquakes. The resulting predictive equations show amplification of the response values at soil sites for periods greater than or equal to 0.5 s, with maximum amplification exceeding a factor of 2 at 1.5s. For periods less than 0.5 s there is no statistically significant difference between rock sites and the soil sites represented in the data set. These results are consistent with those of several earlier studies. A particularly significant aspect of the predictive equations is that the response values at different periods are different functions of magnitude (confirming earlier results by McGuire and by Trifunac and Anderson). The slope of the least-squares straight line relating log response to moment magnitude ranges from 0.21 at a period of 0.1 s to greater than 0.5 at periods of 1 s and longer. This result indicates that the conventional practice of scaling a constant spectral shape by peak acceleration will not give accurate answers. The Newmark and Hall method of spectral scaling, using both peak acceleration and peak velocity, largely avoids this error. Comparison of our spectra with the Regulatory Guide 1.60 spectrum anchored at the same value at 0.1 s shows that the Regulatory Guide 1.60 spectrum is exceeded at soil sites for a magnitude of 7.5 at all distances for periods greater than about 0.5 s. Comparison of our spectra for soil sites with the corresponding ATC-3 curve of lateral design force co-efficients for the highest seismic zone indicates that the

ATC-3 curve is exceeded within about 5 km of a magnitude 6.5 earthquake and within about 20 km of a magnitude 7.5 event. The amount by which it is exceeded is largest in the period range from 0.5 to 2.0 s.

INTRODUCTION

Recently acquired strong motion data make possible improved predictions of near-source earthquake ground motion. In a previous paper (Joyner and Boore, 1981) we used those data in developing prediction equations for peak horizontal acceleration and velocity. The present paper gives the corresponding predictive equations for horizontal pseudo-velocity response values at 5 percent damping and 12 different periods from 0.1 to 4.0 s. (The pseudo-velocity response is defined as the angular frequency of the oscillator times the maximum relative displacement response.) These equations enable us to predict response spectra directly without the use of a scaling parameter such as peak acceleration or peak velocity. They also enable us to examine the degree to which the shape of response spectra depends on magnitude, distance, and site conditions--an important issue in engineering seismology in view of the common practice of deriving design spectra by using peak acceleration to scale spectra of constant shape.

METHOD

We fit the response spectral data at each period using a two-step regression analysis. The first step is represented by the equation:

$$\log y_{ij} = a_i - p \log r + b\, r + c\, S_j \qquad (1)$$

where S_j = 1 if site j is a soil site

= 0 if site j is a rock site

$$r = (d_{ij}^2 + h^2)^{1/2}$$

y_{ij} is the pseudo-velocity response value for earthquake i at site j and d_{ij} is the closest distance from recording site j to the vertical projection on the earth's surface of the rupture surface for earthquake i. THe parameters a_i, p, b, c, and h are determined by the regression analysis. In the usual case p is taken to be unity and a_i, b, and c are determined by linear regression for successive assumed values of h. The final values are determined by a simple search procedure on h to minimize the sum of squares of residuals. If the final value obtained for b is positive (which would represent negative anelastic attenuation) we set b equal to zero and redo the process with a_i, p, and c as the parameters determined by linear regression. Once the values of a_i are determined they are used in a second regression analysis to determine the magnitude dependence according to the equation:

$$a_i = \alpha + \beta \mathbf{M}_i \qquad (2)$$

where $\mathbf{M}_i$ is the moment magnitude (Hanks and Kanamori, 1979) of earthquake i. The form chosen for the regression is the equivalent of:

$$y = \frac{k}{r^p} e^{-qr}$$

where k is a function of magnitude and period and q is a function of period.

To estimate σ_y, the standard error of the prediction made by the procedure described here, we use the equation:

$$\sigma_y = (\sigma_s^2 + \sigma_a^2)^{1/2}$$

where σ_s is the standard deviation of the residuals from the regression analysis of equation (1) and σ_a is the standard deviation of the residuals of the regression analysis of equation (2).

DATA

The data set represents 64 records from 12 earthquakes. This is the data set used earlier (Joyner and Boore, 1981) for peak velocity, augmented by three additional records and diminished by one. The three added records are at Sitka, Alaska, on a rock site 45 km from the **M** 7.7 Sitka earthquake of 1972, at Icy Bay, Alaska, on a soil site 25.4 km from the **M** 7.6 St. Elias earthquake of 1979, and at Managua, Nicaragua, on a soil site 5 km from the **M** 6.2 Managua earthquake of 1972. The record removed from the data set is the record from the Oroville, California earthquake of 1975. The filter used in processing that record had a long-period cut off short enough to affect periods within our range of interest. The distribution of the data set in magnitude and distance is shown in Figure 1.

At each period we used the larger of the two horizontal response values. In the future we plan to repeat the analysis for the mean of the two horizontal values.

RESULTS

To illustrate the dependence of the response values on magnitude, the results of the regression analysis of equation (2) are shown in Figures 2, 3, and 4 for periods of 0.1, 0.5, and 1.0 s, respectively. Note that the slope of the line is greater at longer periods.

The result of the two-stage regression analysis is a predictive equation for pseudo-velocity response

$$\log y = \alpha + \beta \mathbf{M} - p \log r + b\, r + c\, S \qquad (3)$$

$$r = (d^2 + h^2)^{1/2}$$

where the symbols are as defined for equation (1) and the parameters

α, β, p, b, c, and h are determined for each period by the two-stage regression analysis in the manner previously described.

Our use of a value of h in equation (3) that is independent of magnitude is the equivalent of assuming that the curve showing the attenuation of response with distance has the same shape independent of magnitude or, in other words, that the change in response for a given change in magnitude is the same at every distance. We used the same assumption in our analysis of peak acceleration (Joyner and Boore, 1981). Others (e.g., Campbell, 1981) in analyzing peak acceleration have postulated that the shape of the attenuation curve does in fact change with magnitude and in particular that at small source distances there is less change in peak acceleration for a given change in magnitude than at large distances. We test this proposition for response spectra in the same way we tested it for peak acceleration and velocity (Joyner and Boore, 1981). We take stations with source distances less than 10 km, which are the ones most sensitive to a magnitude dependent attenuation, and we compute the residuals against the predictive equations based on the assumption of magnitude-independent attenuation. We then plot the residuals against magnitude. If there is support in the data for magnitude-dependent attenuation, it should show as a magnitude dependence in those residuals. The residuals are plotted against magnitude along with the least-squares straight line in Figures 5, 6, and 7 for periods of 0.1, 0.5 and 1.0 s, respectively. These plots do not suggest any systematic relationship. The slope of the least-squares straight line in Figure 5 indicates a greater change at small distances for a given change in magnitude rather than less. We conclude that there is no support in the data for an attenuation curve with magnitude-dependent shape.

Carrying out the analysis for response at 5 percent damping gives the parameters required by equation (3). These are plotted against period in Figure 8. Because we believe that smooth spectra will be more useful, we draw smooth curves for the points in Figure 8, and use the smoothed values for all spectra shown. Both raw and smoothed values of the parameters are given in Table 1.

Figure 9 shows the spectra for rock and soil sites at zero distance and moment magnitudes of 5.5, 6.5, and 7.5. A large effect of magnitude on spectral shape is indicated by the different spacing at short and long periods between the curves for different magnitudes. The same result is implicit in Figure 8 which shows that the magnitude coefficient ranges from less than 0.25 at the short period end to more than 0.50 at the long period end. Earlier work by McGuire (1974) and by Trifunac and Anderson (1978) demonstrated this general relationship between response values and magnitude.

Figure 9 indicates a dependence of spectral shape on site conditions in that there is an amplification by about a factor of two at soil sites for the longer periods and no amplification at all for the shorter periods. These results are similar to those of several earlier studies and certainly hold for the typical soil site represented in our data set, but caution should be exercised in applying the results, because there is evidence that substantial amplification does occur at short periods for certain site conditions. In the 1979 Coyote Lake earthquake, records were obtained at a rock site and at a site only two kilometers away where 180 m of Quaternary alluvium overlay the rock (Joyner and others, 1981). The pseudo-velocity response at 0.1 s and 5 percent damping was amplified by a factor of 1.9 at the site on alluvium. A likely explanation of the discrepancy is that there is a much greater thickness of low-Q material at the typical soil site, and therefore more attenuation of high frequencies than at the site referred to above.

Figure 10 shows the spectra for soil sites at magnitude 7.5 and a range of distances. The shape of the spectrum changes significantly between d = 0 and 10 km but relatively little between 10 km and 40 km. The difference in shape between 0 and 10 km reflects the fact that the h values at shorter periods are about twice as great as those for longer periods. A corresponding relationship was found between the h values for peak horizontal acceleration and velocity (Joyner and Boore, 1981).

DISCUSSION

Equation (3) along with the parameter values given in Table 1 constitutes a set of equations by which response spectra can be predicted directly without the use of scaling parameters such as peak acceleration or peak velocity. These equations are constrained by data at soil sites over the entire distance range of interest for moment magnitudes less than or equal to 6.5. The data set contains no recording at rock sites with d less than 8 km for earthquakes with magnitude greater than 6.0, and caution should be used in applying the equations to rock sites at shorter distances for earthquakes of larger magnitudes. For distances less than 25 km and magnitudes greater than 6.6 the predictive equations are not constrained by data, and there also the results should be treated with caution. We do not propose use of the predictive equations beyond a moment magnitude of 7.7, the limit of the data set.

The result that the shape of response spectra depends strongly on magnitude indicates that the common practice of using peak acceleration to scale normalized spectra of fixed shape leads to substantial error. The coefficient of magnitude in the predictive equation for peak horizontal acceleration is approximately 0.25 and the corresponding coefficients for the response spectral values at periods greater than 1.0 s are all greater than 0.50. Most of the records used in determining standard spectral shapes are from earthquakes of magnitude less than 7.0; the average might be 6.5 or less. Under these circumstances the practice of scaling a standard spectral shape using peak acceleration would result in an error of about a factor of two at magnitude 7.5 for periods greater than 1.0 s.

The scaling procedure advocated by Newmark and Hall (1969) is largely immune from the errors associated with scaling standard spectral shapes by peak acceleration. They suggested scaling the short period portion of the spectrum by peak acceleration and the intermediate portion (about 0.3 to 2.0 s) by peak velocity. Comparison of the parameter values in Figure 8 and Table 1 with the corresponding values for peak horizontal acceleration and velocity (Joyner and Boore, 1981) indicates a general similarity between the parameter values for short period response and those for peak acceleration and between the values for longer period response and those for peak velocity.

The design of nuclear power facilities in the United States is largely on the basis of a fixed spectral shape described in Regulatory Guide 1.60 (U. S. Atomic Energy Commission, 1973). It is intended that this spectral shape be scaled by peak acceleration. Regulatory Guide 1.60 specifies that it does not apply to sites which "(1) are relatively close the the epicenter of an expected earthquake or (2) have physical characteristics that could significantly affect the spectral pattern of input motion, such as being underlain by poor soil deposits." No quantitative definitions of "close to the epicenter" or "poor soil deposits" are given. We compare the Regulatory Guide 1.60 spectrum with our spectra in Figures 11 and 12. Figure 11 gives spectra for soil sites for a moment magnitude of 6.5 and distances of 0, 10, and 40 km. Figure 12 gives the corresponding spectra for a magnitude of

7.5. The Regulatory Guide 1.60 spectrum is shown by the dashed line and for the purpose of comparison is anchored to each of our spectra at a period of 0.1 s. On Figure 11 the Regulatory Guide 1.60 spectrum is exceeded only by our spectrum for zero distance. Even that is not a problem, however, because the Regulatory Guide 1.60 spectrum is not intended for use at "close" distance. On Figure 12 we see that for magnitude 7.5 the Regulatory Guide 1.60 spectrum is substantially exceeded at all distances for periods greater than about 0.5 s. Whether this represents a serious problem or not depends of course upon whether there are important structures with periods greater than 0.5 s and upon the safety margins available.

The lateral-force coefficients in the earthquake-resistance provisions of buiding codes can be related to response spectra. In Figures 13 and 14 we compare our spectra with the lateral design force coefficient C_s in the proposed ATC-3 code (Applied Technology Council, 1978). Figure 13 gives our spectra at soil sites and a range of distances for a magnitude of 6.5, and Figure 14 gives the corresponding spectra for magnitude 7.5. The C_s curve from ATC-3, shown in both Figures 13 and 14 by the dashed line, is calculated for a response modification factor R of 1.0, for soil type S2 (deep cohesionless or stiff clay soil conditions) and for A_a and A_v values of 0.4, which correspond to the zones of greatest expected ground motion. The comparisons show that the ATC-3 curve is exceeded within about 5 km of a magnitude 6.5 earthquake and within about 20 km of a magnitude 7.5 event. The amount by which it is exceeded is largest in the period range from 0.5 to 2.0s. The implications of these differences depend among other things upon the safety margins available in the system and can only be properly evaluated by structural engineers.

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Table 1. Parameters in the Prediction Equations for Pseudo-Velocity Response (cm/s) at 5 Percent Damping.

Period s		α	β	h km	p	b km^{-1}	c	σ_y
0.1	raw	0.81	0.210	9.4	1.0	-0.00612	0.0	0.26
	smoothed	0.95	0.210	10.6	1.0	-0.00707	0.0	0.27
0.15	raw	1.07	0.221	11.4	1.0	-0.00766	0.0	0.28
	smoothed	1.09	0.218	10.4	1.0	-0.00661	0.0	0.27
0.2	raw	1.13	0.226	10.8	1.0	-0.00637	0.0	0.27
	smoothed	1.09	0.232	9.7	1.0	-0.00628	0.0	0.27
0.3	raw	0.89	0.276	6.9	1.0	-0.00480	0.0	0.27
	smoothed	0.87	0.280	6.9	1.0	-0.00583	0.0	0.28
0.4	raw	0.39	0.358	4.6	1.0	-0.00519	0.0	0.32
	smoothed	0.41	0.352	5.0	1.0	-0.00551	0.03	0.31
0.5	raw	0.11	0.390	4.7	1.0	-0.00543	0.14	0.33
	smoothed	0.08	0.401	4.5	1.0	-0.00523	0.08	0.33
0.75	raw	-0.52	0.478	3.3	1.0	-0.00451	0.19	0.34
	smoothed	-0.47	0.479	4.4	1.0	-0.00470	0.19	0.36
1.0	raw	-0.72	0.519	5.0	1.0	-0.00548	0.21	0.37
	smoothed	-0.80	0.523	4.4	1.0	-0.00429	0.25	0.36
1.5	raw	-0.93	0.528	5.6	1.0	-0.00310	0.33	0.37
	smoothed	-1.14	0.564	4.4	1.0	-0.00358	0.31	0.36
2.0	raw	-1.44	0.611	5.2	1.0	-0.00327	0.30	0.36
	smoothed	-1.26	0.574	4.4	1.0	-0.00259	0.32	0.36
3.0	raw	-1.37	0.573	3.7	1.0	0.0	0.31	0.33
	smoothed	-1.37	0.576	4.4	1.0	0.0	0.29	0.36
4.0	raw	-1.29	0.554	4.1	0.982	0.0	0.22	0.37
	smoothed	-1.44	0.576	4.4	0.982	0.0	0.25	0.36

Figure 1. Distribution of the data set in moment magnitude and distance.

Figure 2. Values of a_i for horizontal pseudo-velocity response (cm/s) at 5 percent damping and 0.1 s period from the regression analysis of equation (1), plotted against moment magnitude.

Figure 3. Values of a_i for horizontal pseudo-velocity response (cm/s) at 5 percent damping and 0.5 s period from the regression analysis of equation (1), plotted against moment magnitude.

Figure 4. Values of a_i for horizontal pseudo-velocity response (cm/s) at 5 percent damping and 1.0 s period from the regression analysis of equation (1) plotted against moment magnitude.

Figure 5. Residuals with respect to equation (3) of the logarithm of horizontal pseudo-velocity response at 5 percent damping and 0.1 s period plotted against moment magnitude for stations with d less than or equal to 10 km, with least-squares straight line superposed.

Figure 6. Residuals with respect to equation (3) of the logarithm of horizontal pseudo-velocity response at 5 percent damping and 0.5 s period plotted against moment magnitude for stations with d less than or equal to 10 km, with least-squares straight line superposed.

Figure 7. Residuals with respect to equation (3) of the logarithm of horizontal pseudo-velocity response at 5 percent damping and 1.0 s period plotted against moment magnitude for stations with d less than or equal to 10 km, with least-squares straight line superposed.

Figure 8. The parameters of equation (3) plotted against period (except for the parameter p, which is given in Table 1). The solid circles show the values determined by the two-stage regression analysis and the solid lines show the smoothed values.

Figure 9. Predicted pseudo--velocity response spectra for 5 percent damping at rock sites (dashed line) and soil sites (solid line) for d equal to zero and moment magnitude equal to 5.5, 6.5 and 7.5.

Figure 10. Predicted pseudo--velocity resonse spectra for 5 percent damping at soil sites for a moment magnitude of 7.5 and d equal to 0, 5, 10, 20, and 40 km.

Figure 11. Predicted pseudo--velocity response spectra for 5 percent damping (solid lines) at soil sites for a moment magnitude of 6.5 and d equal to 0, 10, and 40 km compared to the Regulatory Guide, 1.60 spectrum (dashed lines) anchored to the predicted spectra at 0.1 s.

Figure 12. Predicted pseudo--velocity response spectra for 5 percent damping (solid lines) at soil sites for a moment magnitude of 7.5 and d equal to 0, 10, and 40 km compared to the Regulatory Guide 1.60 spectrum (dashed lines) anchored to the predicted spectra at 0.1 s.

Figure 13. Predicted pseudo--velocity response spectra for 5 percent damping (solid lines) at soil sites for a moment magnitude of 6.5 and d equal to 0, 5, 10, 20 and 40 km compared to the ATC-3 lateral design force coefficient (dashed line) calculated for a response modification factor R of 1.0, for soil type S2, and for A_a and A_v of 0.4.

Figure 14. Predicted pseudo--velocity response spectra for 5 percent damping (solid lines) at soil sites for a moment magnitude of 7.5 and d equal to 0, 5, 10, 20, and 40 km compared to the ATC-3 lateral design force coefficient (dashed line) calculated for a response modification factur R of 1.0, for soil type S2, and for A_a and A_v of 0.4.

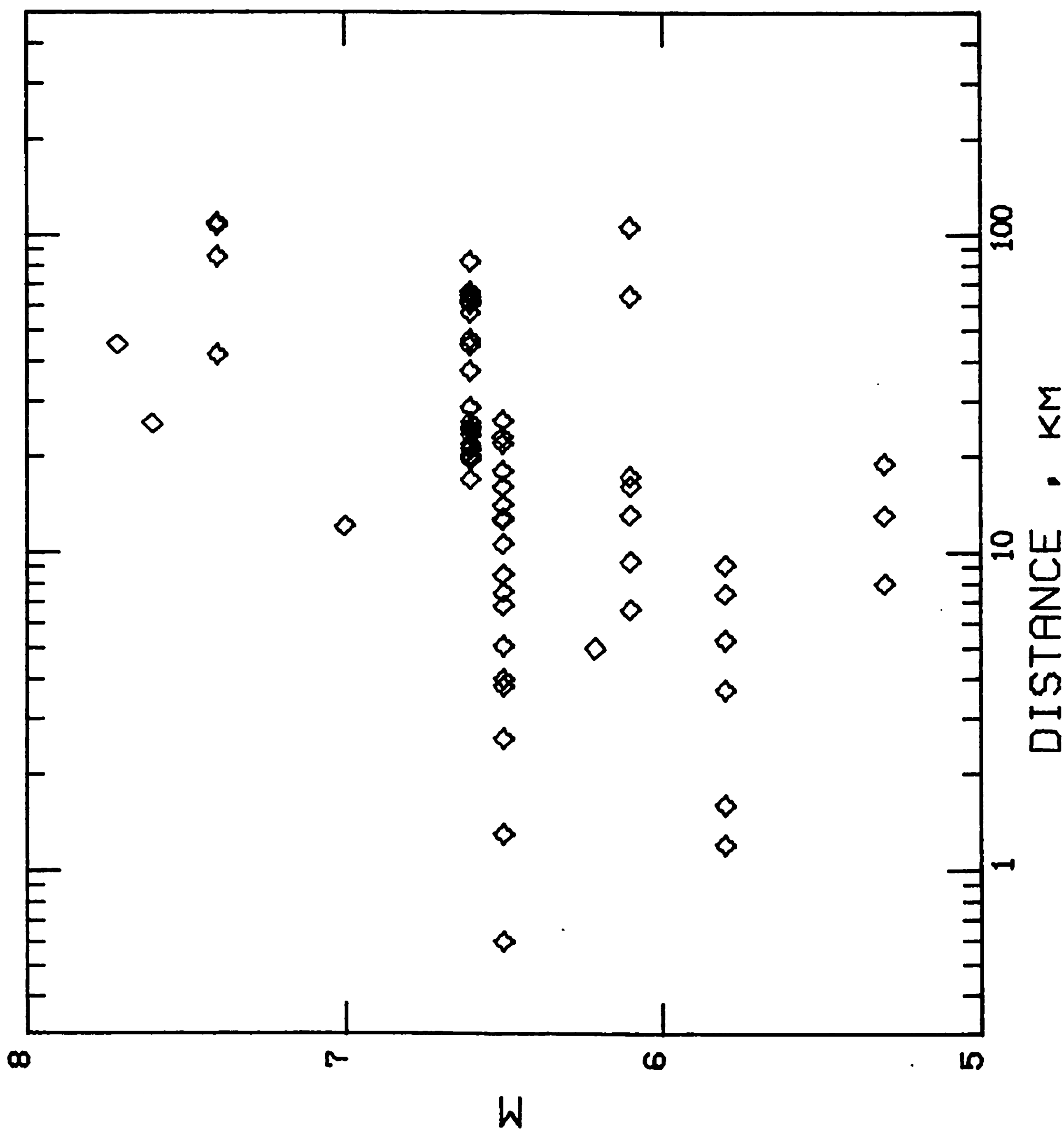


Figure 1

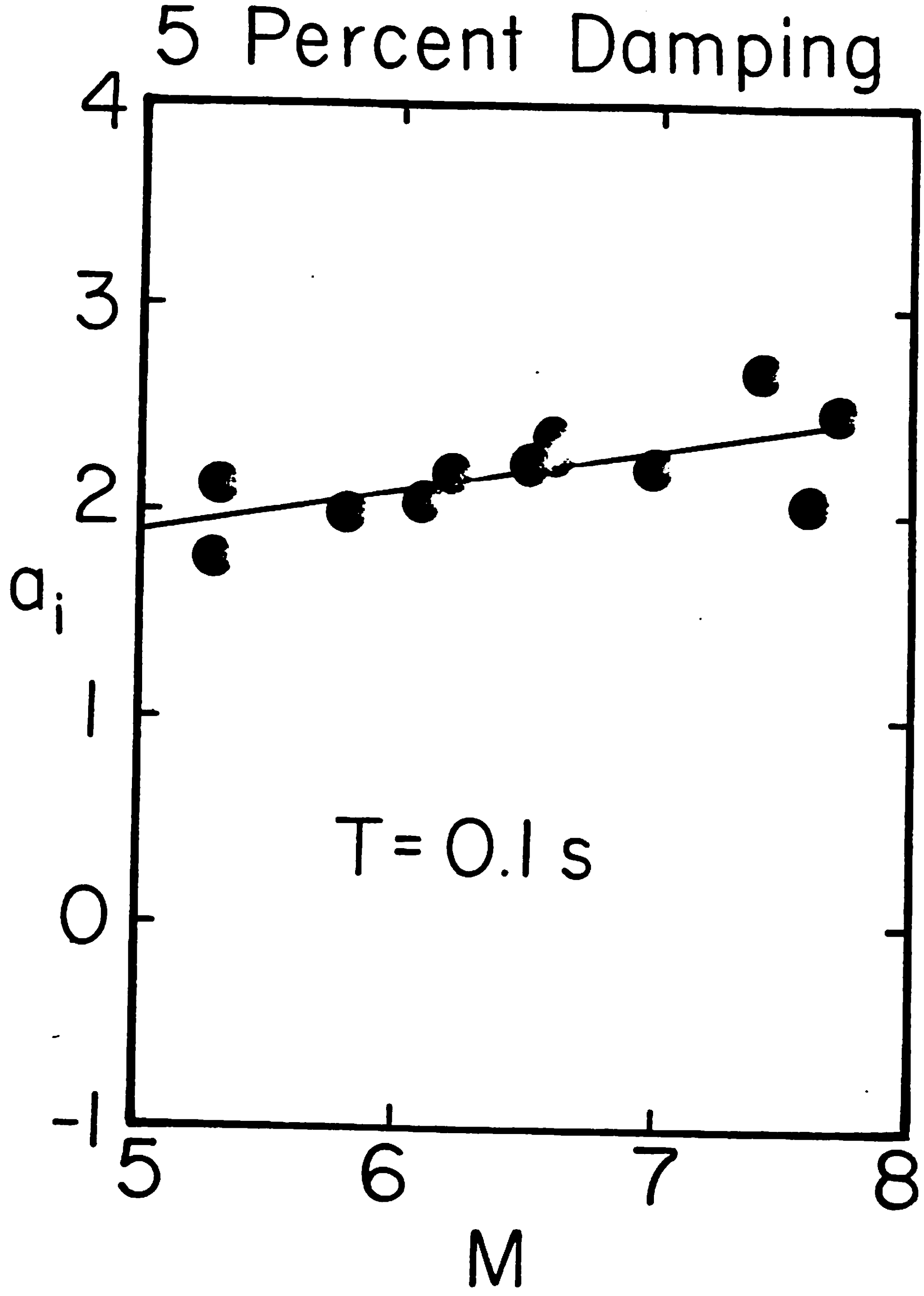
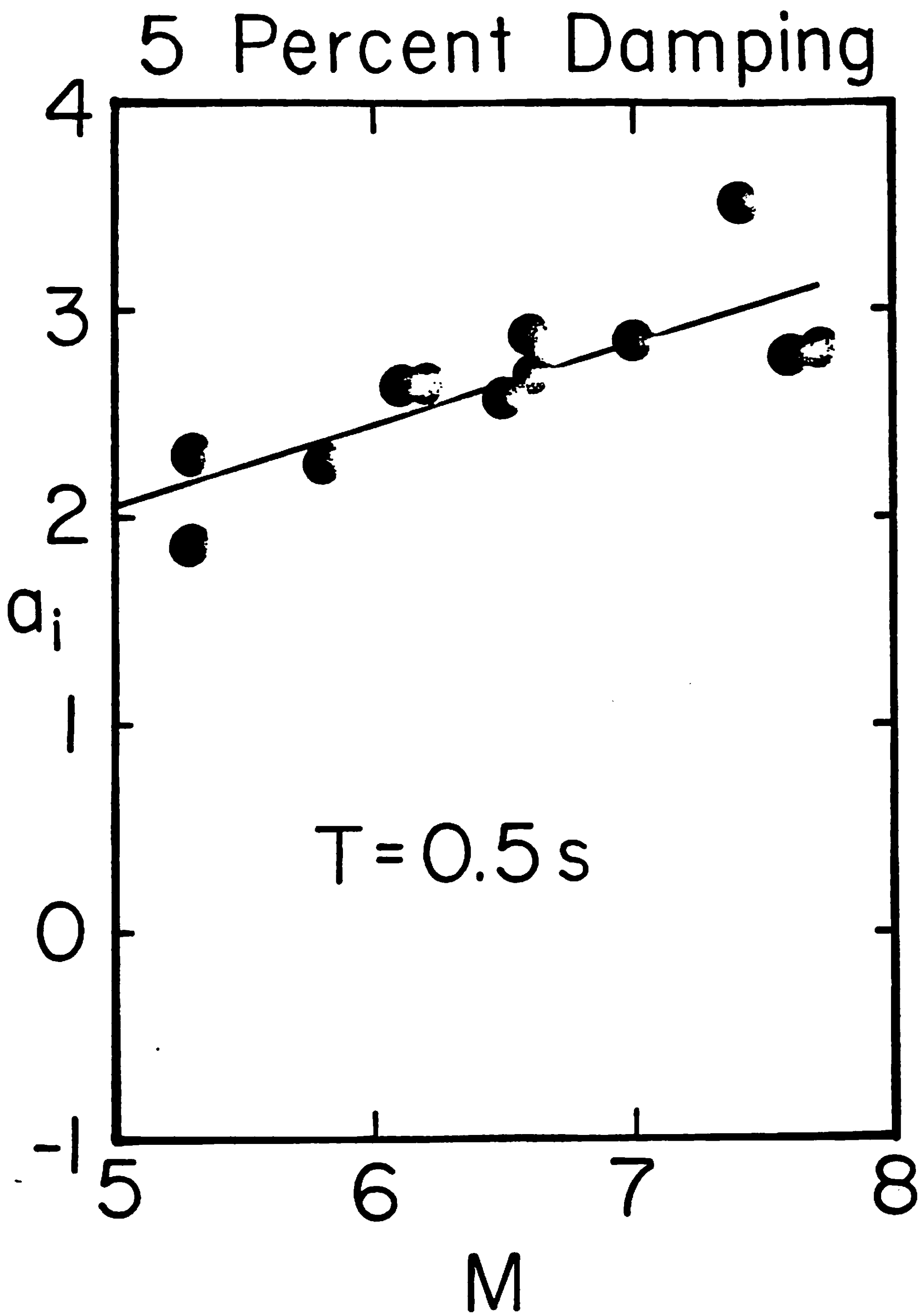


Figure 2



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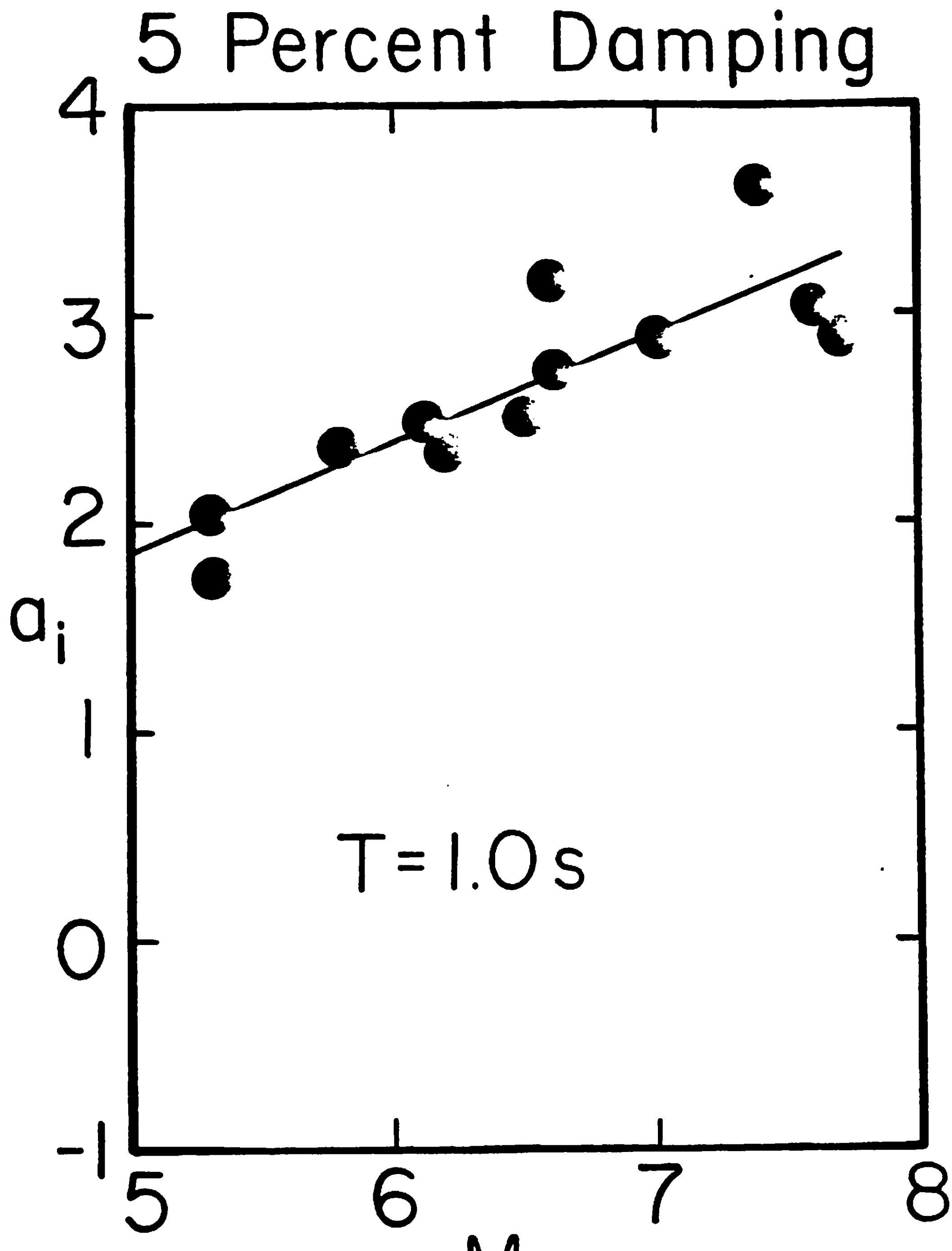

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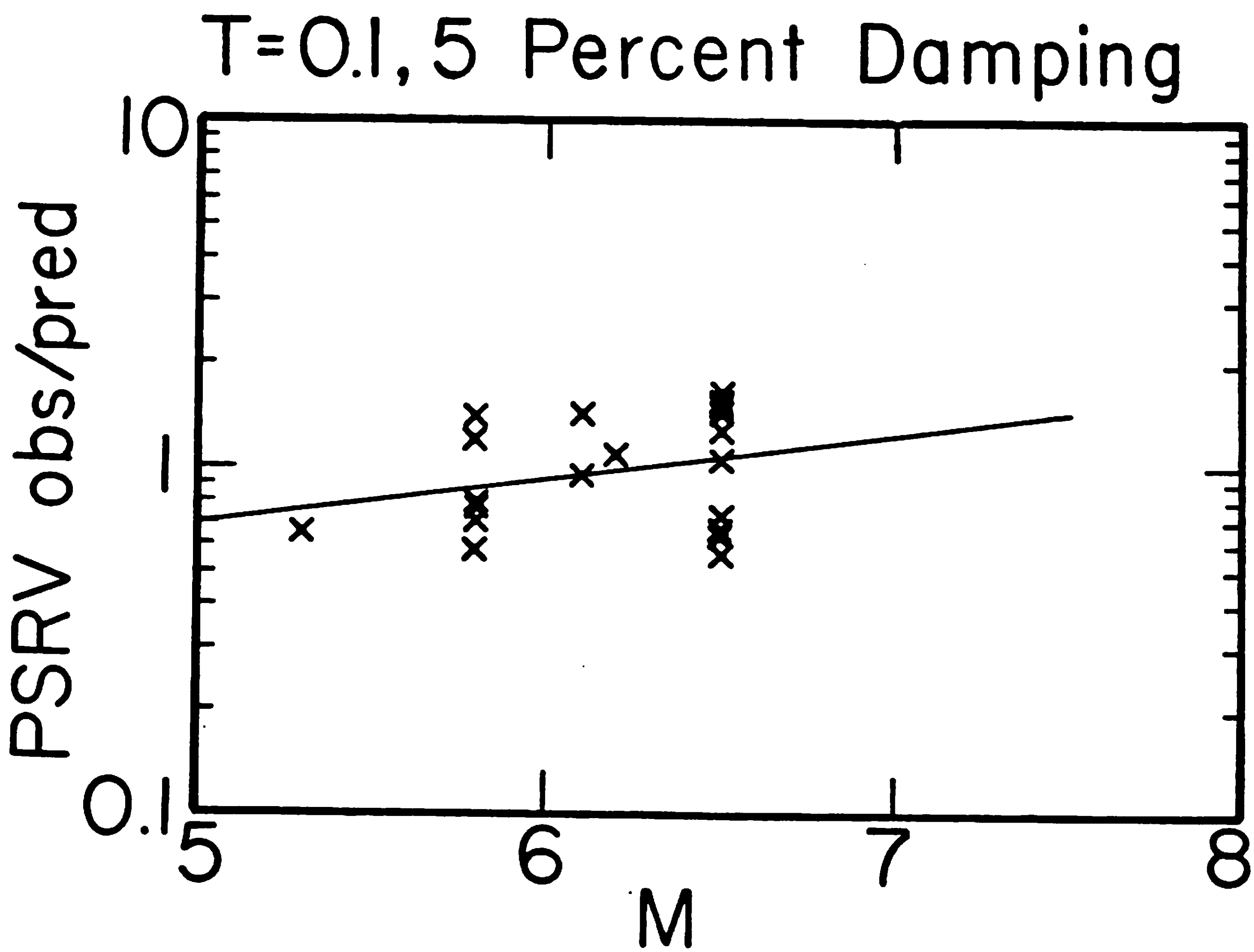

Figure 5

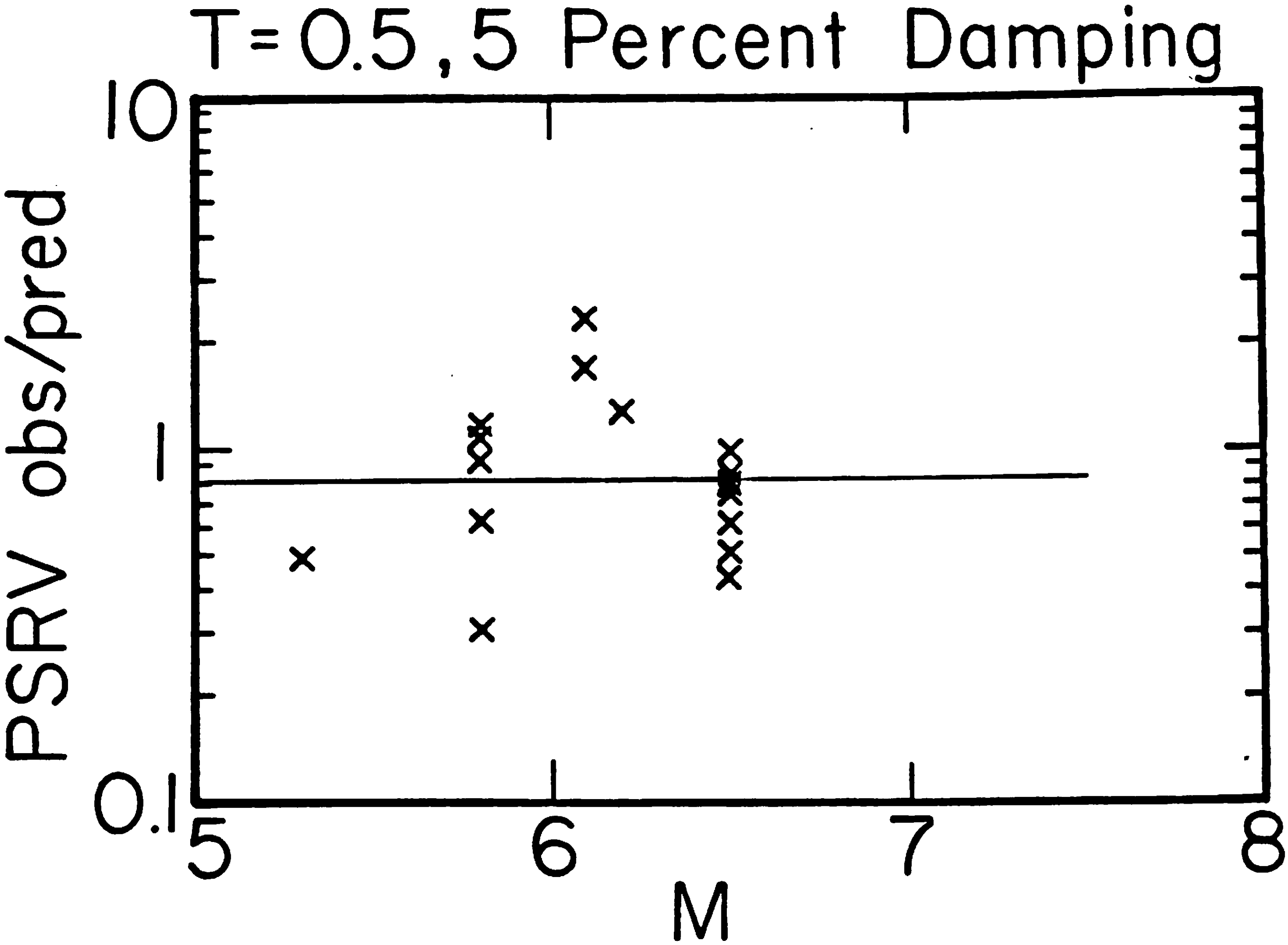

Figure 6

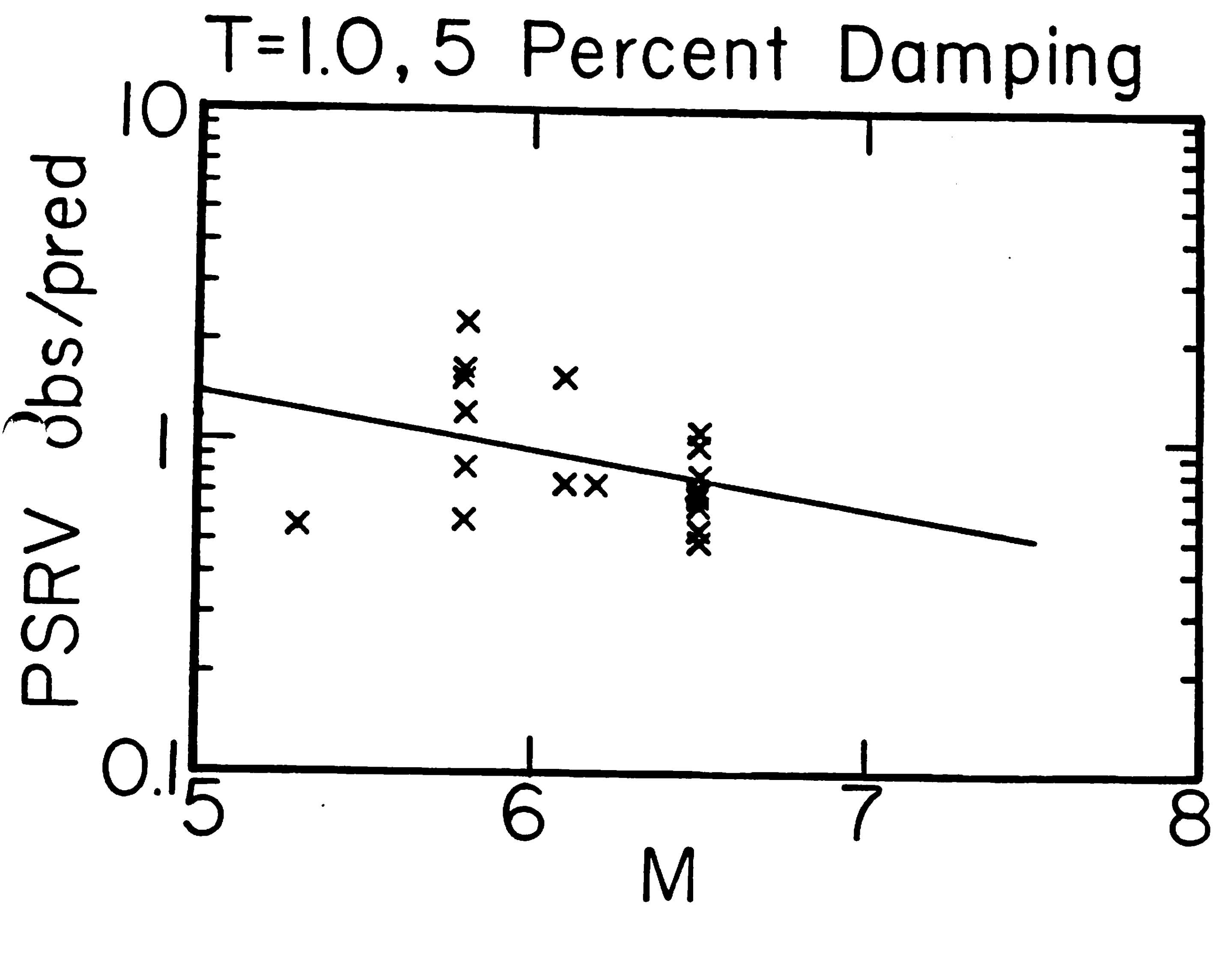

Figure 7