PREDICTION OF EARTHQUAKE RESPONSE SPECTRA

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ABSTRACT

We have developed empirical equations for predicting earthquake response spectra in terms of magnitude, distance, and site conditions, using a two-stage regression method similar to the one we used previously for peak horizontal acceleration and velocity. We analyzed horizontal pseudo-velocity response at 5 percent damping for 64 records of 12 shallow earthquakes in Western North America, including the recent Coyote Lake and Imperial Valley, California, earthquakes. We developed predictive equations for 12 different periods between 0.1 and 4.0 s, both for the larger of two horizontal components and for the random horizontal component. The resulting spectra show amplification at soil sites compared to rock sites for periods greater than or equal to 0.3 s, with maximum amplification exceeding a factor of 2 at 2.0 s. For periods less than 0.3 s there is slight deamplification at the soil sites. These results are generally consistent with those of several earlier studies. A particularly significant aspect of the predicted spectra is the change of shape with magnitude (confirming earlier results by McGuire and by Trifunac and Anderson). 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 Nuclear Regulatory Commission's 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 coefficient for the highest seismic zone indicates that the ATC-3 curve is exceeded within about 7 km of a magnitude 6.5 earthquake and within about 15 km of a magnitude 7.5 event. The amount by which it is exceeded for the 7.5 event is largest in the period range from 0.5 to 2.0 s.

INTRODUCTION

The response spectrum is a basic element, either directly or indirectly, in earthquake resistant design. It is used directly as input in the dynamic analysis of structures and indirectly as the basis for the relationship between the lateral design force coefficient and period. The conventional method for arriving at estimates of the response spectrum is first to estimate the peak acceleration and then use the peak acceleration to scale some normalized spectral shape such as the Nuclear Regulatory Commission's Regulatory Guide 1.60 spectrum (Ref. 10). Such a procedure will be valid only to the extent that the shape of the response spectrum is independent of earthquake magnitude, source distance, and recording site conditions. To avoid this problem, Newmark and Hall (Ref. 8) recommended a modified method of estimating the response spectrum in which the short periods are scaled by peak acceleration, intermediate periods by peak velocity, and long periods by peak displacement. The ideal approach is to develop methods for estimating response values directly without using scaling factors such as peak acceleration. This was done by McGuire (Ref. 7) and by Trifunac and Anderson (Ref. 9).

Until recently efforts to predict response values, peak acceleration, or any strong-motion parameters, for that matter, were handicapped by the scarcity of strong motion records close to the source of moderate or major earthquakes. Recent events, particularly the 1979 Coyote Lake (magnitude 5.8) and Imperial Valley (magnitude 6.5) earthquakes in California, have significantly improved the strong motion data set at small source distances, and prediction equations incorporating the new data have been developed for peak horizontal acceleration (Refs. 3, 5) and for peak horizontal velocity (Ref. 5). In this paper we present preliminary results in the development of equations for the direct prediction of response spectral values. We show in particular how the shape of response spectra depends on magnitude, distance, and site conditions. This paper is an expansion of an earlier study (Ref. 6).

THE PREDICTION EQUATIONS

The data set is restricted to earthquakes in western North America with moment magnitude (Ref. 4) greater than 5.0 and to shallow earthquakes, defined as those for which the fault rupture lies mainly above a depth of 20 km. The data set includes 64 records from 12 earthquakes and is similar to the data set used earlier (Ref. 5) for peak velocity, the principal change being the addition of records from the moment magnitude 7.7 Sitka, Alaska, earthquake of 1972 and the moment magnitude 7.6 St. Elias, Alaska, earthquake of 1979. The distribution of the data set in magnitude and distance is shown in Fig. 1. Using a two-stage regression procedure described elsewhere (Refs. 5, 6) we fit the data with the equation:

$$\log y = \alpha + \beta(M - 6) + \gamma(M - 6)^2 - p \log r + b r + c S \qquad (1)$$

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

where y is the response spectral value at a given period, M is moment magnitude, S takes on the value 1 for a soil site and 0 for a rock site, and d is the closest distance from the recording site to the vertical projection on the earth's surface of the rupture surface for the earthquake. The parameters α, β, γ, p, b, c, and h are determined for each period by the regression analysis. The parameter h is a fictitious depth introduced to allow for the fact that the source of the maximum response may not be the closest point on the rupture surface. The value obtained for h incorporates all the factors that tend to limit (or enhance) motion near the source. The analysis was done for 12 different periods between 0.1 and

4.0 s, the upper limit of 4.0 s being chosen to avoid problems with record-processing errors at long periods.

The use in equation (1) of a value of h 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 have examined the data for peak horizontal acceleration, velocity, and response spectra and do not find support for a magnitude-dependent shape (Refs. 2, 5, 6). Campbell (Ref. 3) arrives at a different conclusion with respect to peak horizontal acceleration. In spite of this difference and others in assumptions and method, however, his predictions and ours differ by amounts small compared to the statistical uncertainty.

Equation (1) includes a quadratic term in magnitude and in that respect differs from the equation we used earlier (Ref. 6) for predicting response spectra. For most periods the coefficient of the quadratic term is not statistically significant at the 90 percent level, but the values obtained at different periods are sufficiently consistent to convince us that inclusion of the quadratic term is warranted. The maximum resulting difference in predicted values, with and without the quadratic term, is about 20 percent. On the same basis we include the soil term at short periods where the coefficient is not significant at the 90 percent level.

Table 1 gives the parameters of the prediction equation for the larger of two horizontal components of pseudo-velocity response at 5 percent damping. (The pseudo-velocity response is defined as the product of the angular frequency of the oscillator and the maximum relative displacement response.) The estimated standard deviation of an individual prediction, σ_y, is also given in Table 1. Because we believed that smooth spectra would be more useful, we plotted the parameters against the logarithm of period and drew smooth curves. Both raw and smoothed values are given in Table 1. Modifications of the data set have changed the coefficients in the prediction equations given earlier (Ref. 5) for peak horizontal acceleration and velocity and the new coefficients are included in Table 1. The changes for peak acceleration are small, only 10 percent for magnitude 7.5 at zero distance, but for peak velocity, with the addition of two earthquakes of magnitude greater than 7.5, the changes are more substantial, about 20 percent for magnitude 7.5 at zero distance.

For some purposes the response spectrum representing a random horizontal component may be preferred to the spectrum representing the larger of two horizontal components. We obtain the parameters of the prediction equation for the random horizontal component by the expedient of including both horizontal components in the regression analysis. The results are given in Table 2.

DISCUSSION

The prediction 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 recordings at rock sites with d less than 15 km for earthquakes with magnitude greater than 6.0, and caution should be used in applying the equation to rock sites at shorter distances for earthquakes of larger magnitudes. For distances less than 25 km and magnitudes greater than 7.0, the prediction equations are not constrained by data, and in that case the results should be treated with caution. We do not propose use of the prediction equations beyond a moment magnitude of 7.7, the limit of the data set.

Figure 2 shows the predicted 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 long and short periods between the curves for different magnitudes. The earlier work by McGuire (Ref. 7) and by Trifunac and Anderson (Ref. 9) demonstrated this general relationship between response values and magnitude. The change in shape of response spectra with magnitude as shown in Fig. 2 indicates that the common practice of using peak acceleration to scale normalized spectra of fixed shape leads to substantial error for large magnitude earthquakes.

The scaling procedure of Newmark and Hall (Ref. 8), referred to previously, 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. Table 1 indicates a general similarity between the parameter values for short period response and those for peak acceleration and between the values for intermediate period response and those for peak velocity.

Figure 2 also indicates a dependence of spectral shape on site conditions in that there is an amplification by about a factor of 2 at soil sites for the intermediate and longer periods and a slight deamplification for the shorter periods. The coefficients representing deamplification at shorter periods are not statistically significant at the 90 percent level. These results on the effect of site conditions are generally similar to the results of several earlier studies.

Figure 3 shows the spectra for soil sites at magnitude 6.5 and a range of distances. The shape of the spectrum changes significantly between d equals 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 at longer periods. A corresponding relationship is found between the h values for peak horizontal acceleration and velocity (Table 1). Figure 4 shows the corresponding spectra for magnitude 7.5.

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 (Ref. 10). 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 to 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 Figs. 5 and 6. Figure 5 gives spectra for soil sites for a moment magnitude of 6.5 and distances of 0, 10, and 40 km. Figure 6 gives the corresponding spectra for a magnitude of 7.5. The Regulatory Guide 1.60 spectrum is shown by the heavy line and for the purpose of comparison is anchored to each of our spectra at a period of 0.1 s. On Fig. 5 the Regulatory Guide 1.60 spectrum is appreciably exceeded only by our spectrum for 0 distance. Even that is not a problem, however, because the Regulatory Guide 1.60 spectrum is not intended for use at "close" distance. On Fig. 6 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 upon whether there are periods of concern greater than 0.5 s and upon the safety margins available. Generally only relatively short periods are of concern for nuclear facilities.

The lateral-force coefficients in the seismic design provisions of building codes can be related to response spectra. In Figs. 7 and 8 we compare our spectra with the lateral design force coefficient C_s in the proposed ATC-3 code (Ref. 1). Figure 7 gives our spectra at soil sites and a range of distances for a magnitude of 6.5, and Fig. 8 gives the corresponding spectra for magnitude 7.5. The C_s curve from ATC-3, shown in both Figs. 7 and 8 by the heavy 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 7 km of a magnitude 6.5 earthquake and within about 15 km of a magnitude 7.5 event. The amount by which the ATC-3 curve is exceeded for magnitude 7.5 is largest in the period range from 0.5 to 2.0 s. The implications of these differences depend among other things upon the safety margins available and upon the nonlinear response of structures. Such matters are the province of structural engineers, and we as seismologists refrain from comment.

ACKNOWLEDGMENTS

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Table 1. Parameters in the prediction equations for the larger of two horizontal components of pseudo-velocity response (cm/s) at 5 percent damping and of peak acceleration and velocity. Values of the parameters γ and c enclosed in parentheses are not statistically significant at the 90 percent level.

Period s		α	β	γ	h km	b	p km^{-1}	c	σ_y
0.1	raw	2.12	0.30	(−0.08)	9.1	−0.0059	1.0	(−0.06)	0.27
	smoothed	2.24	0.30	−0.09	10.6	−0.0067	1.0	−0.06	0.27
0.15	raw	2.46	0.36	(−0.13)	11.0	−0.0074	1.0	(−0.06)	0.28
	smoothed	2.46	0.34	−0.10	10.3	−0.0063	1.0	−0.05	0.27
0.2	raw	2.56	0.37	(−0.13)	10.5	−0.0061	1.0	(−0.05)	0.26
	smoothed	2.54	0.37	−0.11	9.3	−0.0061	1.0	−0.03	0.27
0.3	raw	2.56	0.38	(−0.11)	7.0	−0.0049	1.0	(0.04)	0.26
	smoothed	2.56	0.43	−0.12	7.0	−0.0057	1.0	0.04	0.27
0.4	raw	2.56	0.50	(−0.15)	4.7	−0.0055	1.0	(0.08)	0.30
	smoothed	2.54	0.49	−0.13	5.7	−0.0055	1.0	0.09	0.30
0.5	raw	2.51	0.55	(−0.16)	4.7	−0.0054	1.0	0.14	0.32
	smoothed	2.53	0.53	−0.14	5.2	−0.0053	1.0	0.12	0.32
0.75	raw	2.39	0.59	(−0.11)	3.3	−0.0045	1.0	0.19	0.34
	smoothed	2.46	0.61	−0.15	4.7	−0.0049	1.0	0.19	0.35
1.0	raw	2.46	0.68	(−0.17)	5.0	−0.0055	1.0	0.21	0.36
	smoothed	2.41	0.66	−0.16	4.6	−0.0044	1.0	0.24	0.35
1.5	raw	2.31	0.71	(−0.18)	5.6	−0.0031	1.0	0.33	0.37
	smoothed	2.32	0.71	−0.17	4.6	−0.0034	1.0	0.30	0.35
2.0	raw	2.30	0.79	(−0.18)	5.2	−0.0033	1.0	0.30	0.36
	smoothed	2.26	0.75	−0.18	4.6	−0.0025	1.0	0.32	0.35
3.0	raw	2.12	0.72	(−0.15)	3.7	0.0	1.01	0.31	0.33
	smoothed	2.17	0.78	−0.19	4.6	0.0	1.0	0.29	0.35
4.0	raw	2.12	0.78	−0.22	4.1	0.0	0.98	0.22	0.35
	smoothed	2.10	0.80	−0.20	4.6	0.0	0.98	0.24	0.35
Peak acceleration (g)		0.49	0.23	0.0	8.0	−0.0027	1.0	0.0	0.28
Peak velocity (cm/s)		2.17	0.49	0.0	4.0	−0.0026	1.0	0.17	0.33

Table 2. Parameters in the prediction equations for the random horizontal component of pseudo-velocity response (cm/s) at 5 percent damping. Values of the parameters γ and c enclosed in parentheses are not statistically significant at the 90 percent level.

Period s		α	β	γ	h km	b	p km^{-1}	c	σ_y
0.1	raw	2.04	0.28	(-0.06)	10.0	-0.0068	1.0	(-0.01)	0.28
	smoothed	2.16	0.25	-0.06	11.3	-0.0073	1.0	-0.02	0.28
0.15	raw	2.37	0.30	(-0.09)	11.4	-0.0074	1.0	(-0.02)	0.28
	smoothed	2.40	0.30	-0.08	10.8	-0.0067	1.0	-0.02	0.28
0.2	raw	2.49	0.36	(-0.12)	10.9	-0.0063	1.0	(-0.02)	0.27
	smoothed	2.46	0.35	-0.09	9.6	-0.0063	1.0	-0.01	0.28
0.3	raw	2.43	0.36	(-0.08)	6.9	-0.0052	1.0	0.10	0.28
	smoothed	2.47	0.42	-0.11	6.9	-0.0058	1.0	0.04	0.28
0.4	raw	2.42	0.51	(-0.13)	4.9	-0.0050	1.0	0.10	0.30
	smoothed	2.44	0.47	-0.13	5.7	-0.0054	1.0	0.10	0.31
0.5	raw	2.42	0.57	(-0.15)	4.5	-0.0052	1.0	0.14	0.33
	smoothed	2.41	0.52	-0.14	5.1	-0.0051	1.0	0.14	0.33
0.75	raw	2.26	0.58	(-0.10)	3.4	-0.0043	1.0	0.23	0.33
	smoothed	2.34	0.60	-0.16	4.8	-0.0045	1.0	0.23	0.33
1.0	raw	2.30	0.68	(-0.16)	4.5	-0.0048	1.0	0.27	0.34
	smoothed	2.28	0.67	-0.17	4.7	-0.0039	1.0	0.27	0.33
1.5	raw	2.21	0.76	(-0.20)	5.4	-0.0029	1.0	0.31	0.35
	smoothed	2.19	0.74	-0.19	4.7	-0.0026	1.0	0.31	0.33
2.0	raw	2.18	0.83	-0.22	4.9	-0.0026	1.0	0.32	0.33
	smoothed	2.12	0.79	-0.20	4.7	-0.0015	1.0	0.32	0.33
3.0	raw	2.00	0.82	-0.22	4.7	0.0	0.98	0.33	0.32
	smoothed	2.02	0.85	-0.22	4.7	0.0	0.98	0.32	0.33
4.0	raw	1.96	0.82	-0.27	5.7	0.0	0.95	0.28	0.33
	smoothed	1.96	0.88	-0.24	4.7	0.0	0.95	0.29	0.33

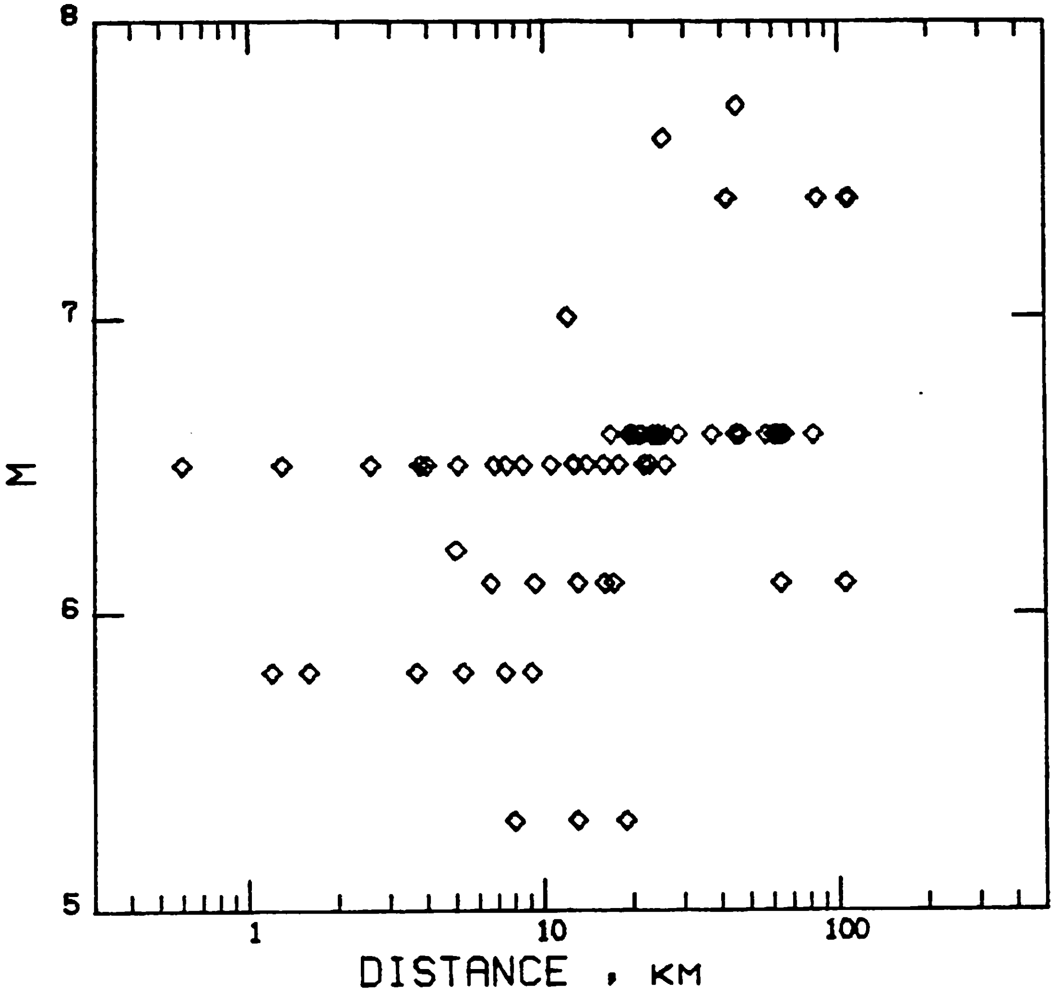

Fig. 1 Distribution of the data set in moment magnitude and distance.

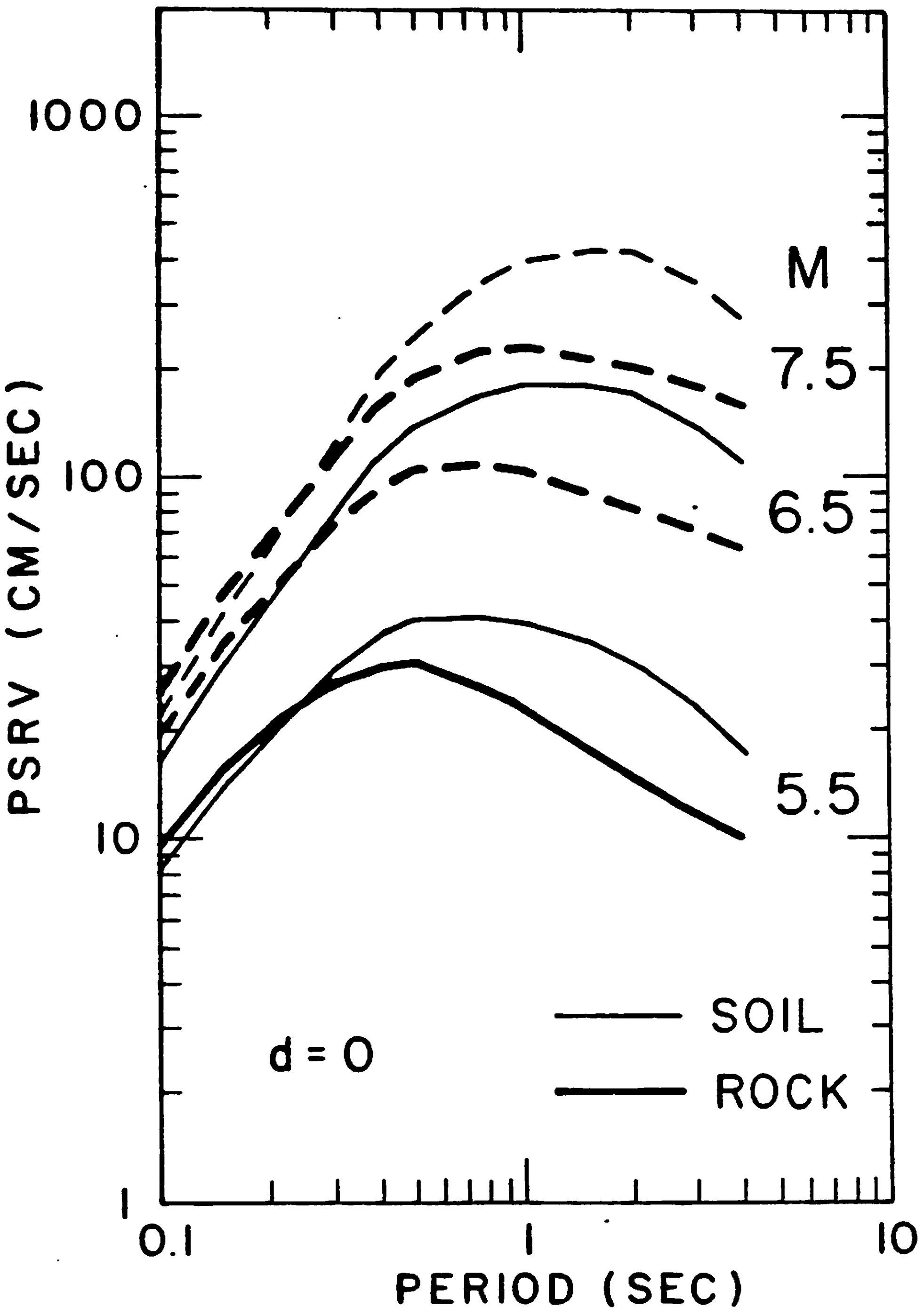

Fig. 2 Predicted pseudo-velocity response spectra for 5 percent damping at rock sites (heavy line) and soil sites (light line) for d equal to zero and moment magnitude equal to 5.5, 6.5, and 7.5. Spectra correspond to the larger of two horizontal components. Curves are dashed where not constrained by data.

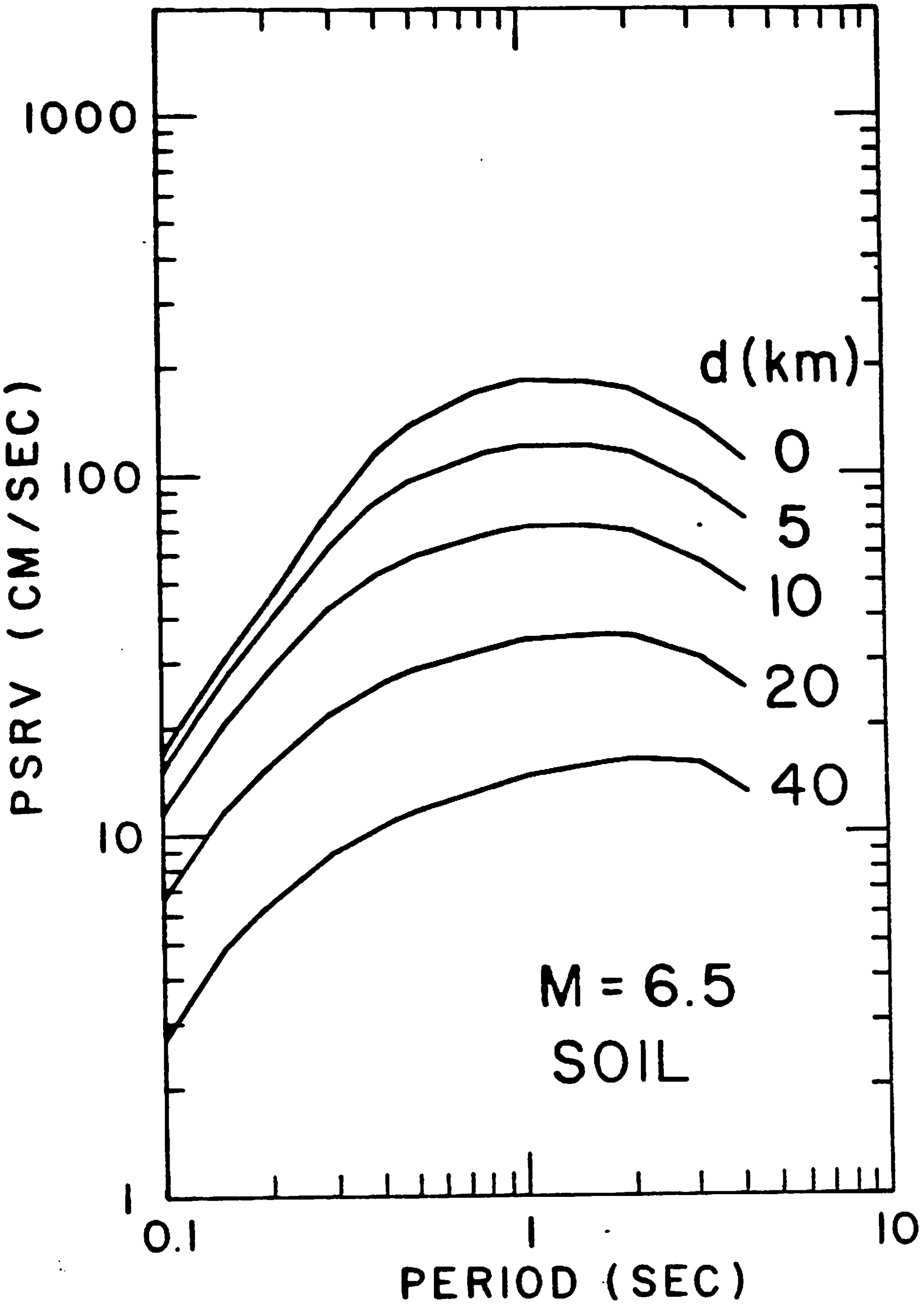

Fig. 3 Predicted pseudo-velocity response spectra for 5 percent damping at soil sites for a moment magnitude of 6.5 and d equal to 0, 5, 10, 20, and 40 km. Spectra correspond to the larger of two horizontal components.

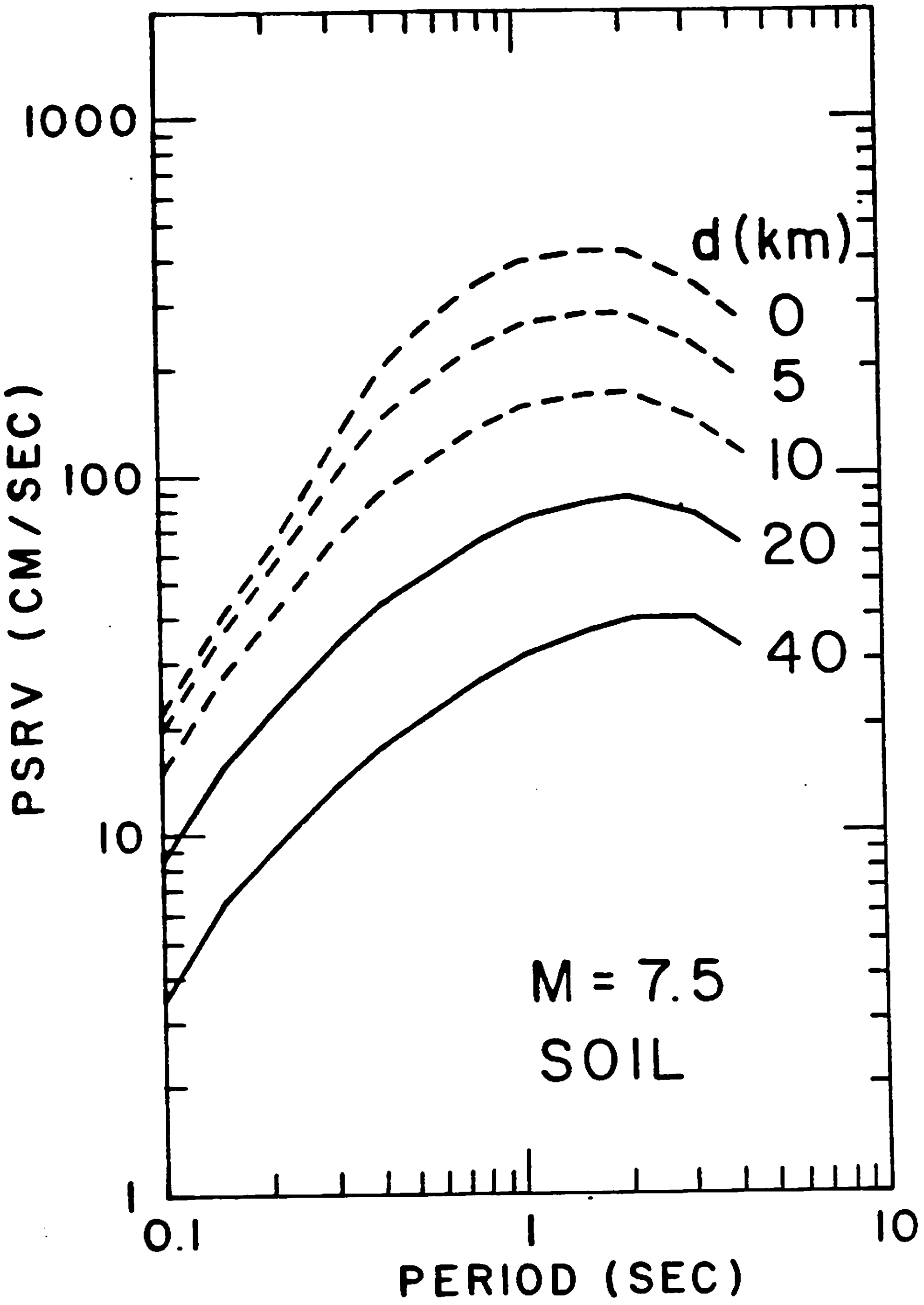

Fig. 4 Predicted pseudo-velocity response spectra for 5 percent damping at soil sites for a moment magnitude of 7.5 and d equal to 0, 5, 10, 20, and 40 km. Spectra correspond to the larger of two horizontal components. Curves are dashed where not constrained by data.

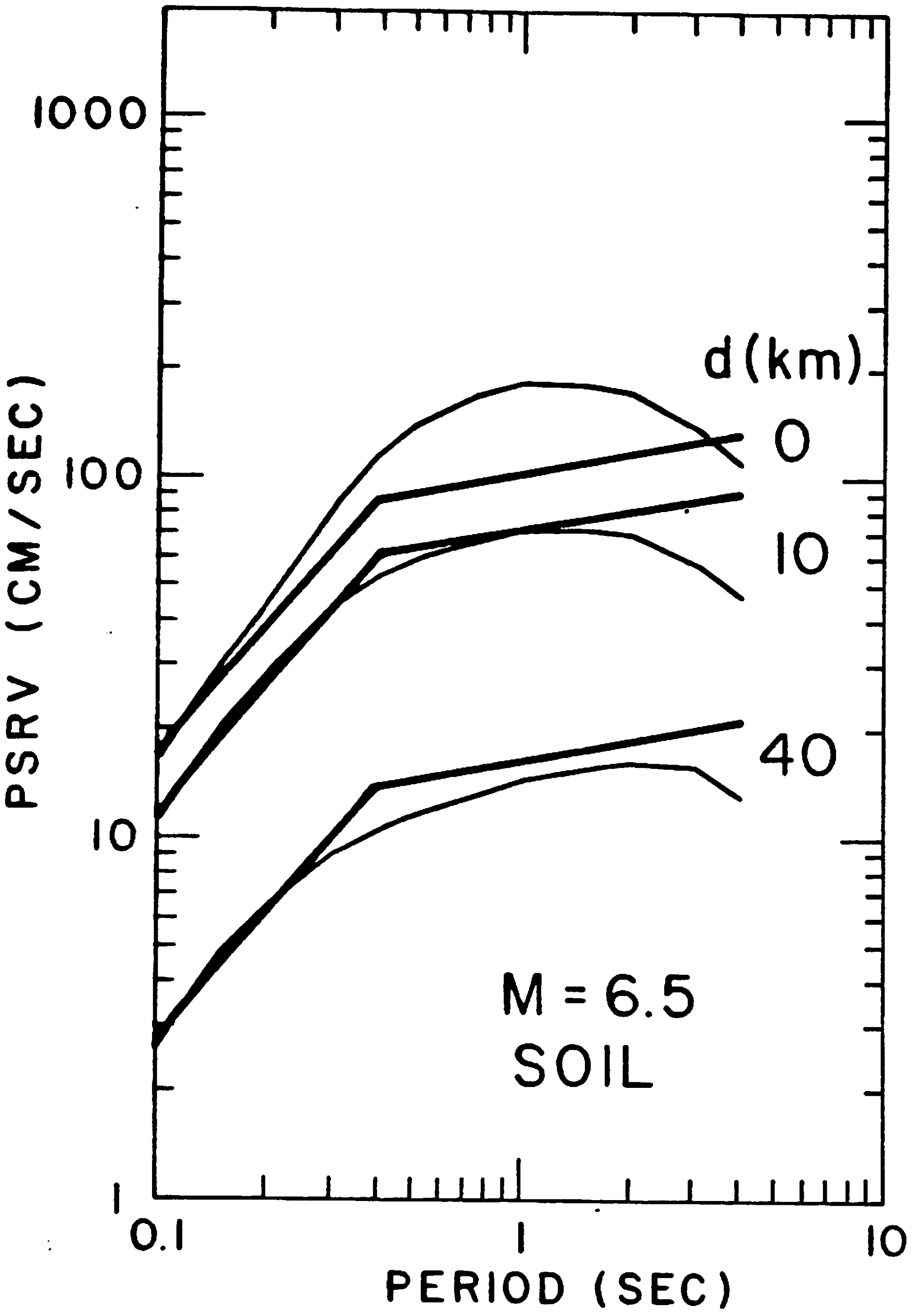

Fig. 5 Predicted pseudo-velocity response spectra for 5 percent damping (light lines) at soil sites for a moment magnitude of 6.5 and d equal to 0, 10, and 40 km compared to the Regulatory Guide 1.60 spectrum (heavy lines) anchored to the predicted spectra at 0.1 s. Predicted spectra correspond to the larger of two horizontal components.

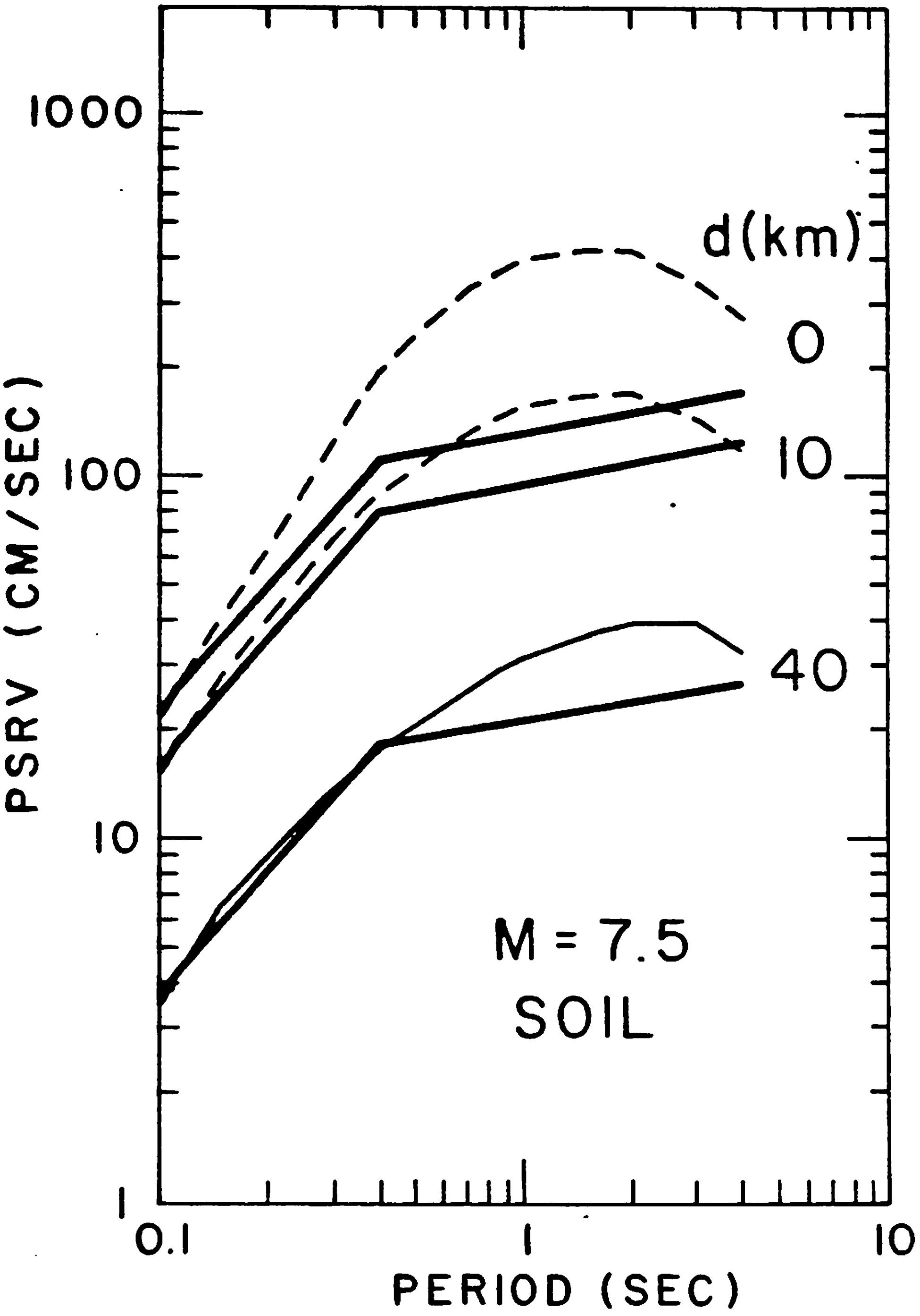

Fig. 6 Predicted pseudo-velocity response spectra for 5 percent damping (light lines) at soil sites for a moment magnitude of 7.5 and d equal to 0, 10, and 40 km compared to the Regulatory Guide 1.60 spectrum (heavy lines) anchored to the predicted spectra at 0.1 s. Predicted spectra correspond to the larger of two horizontal components. Curves are dashed where not constrained by data.

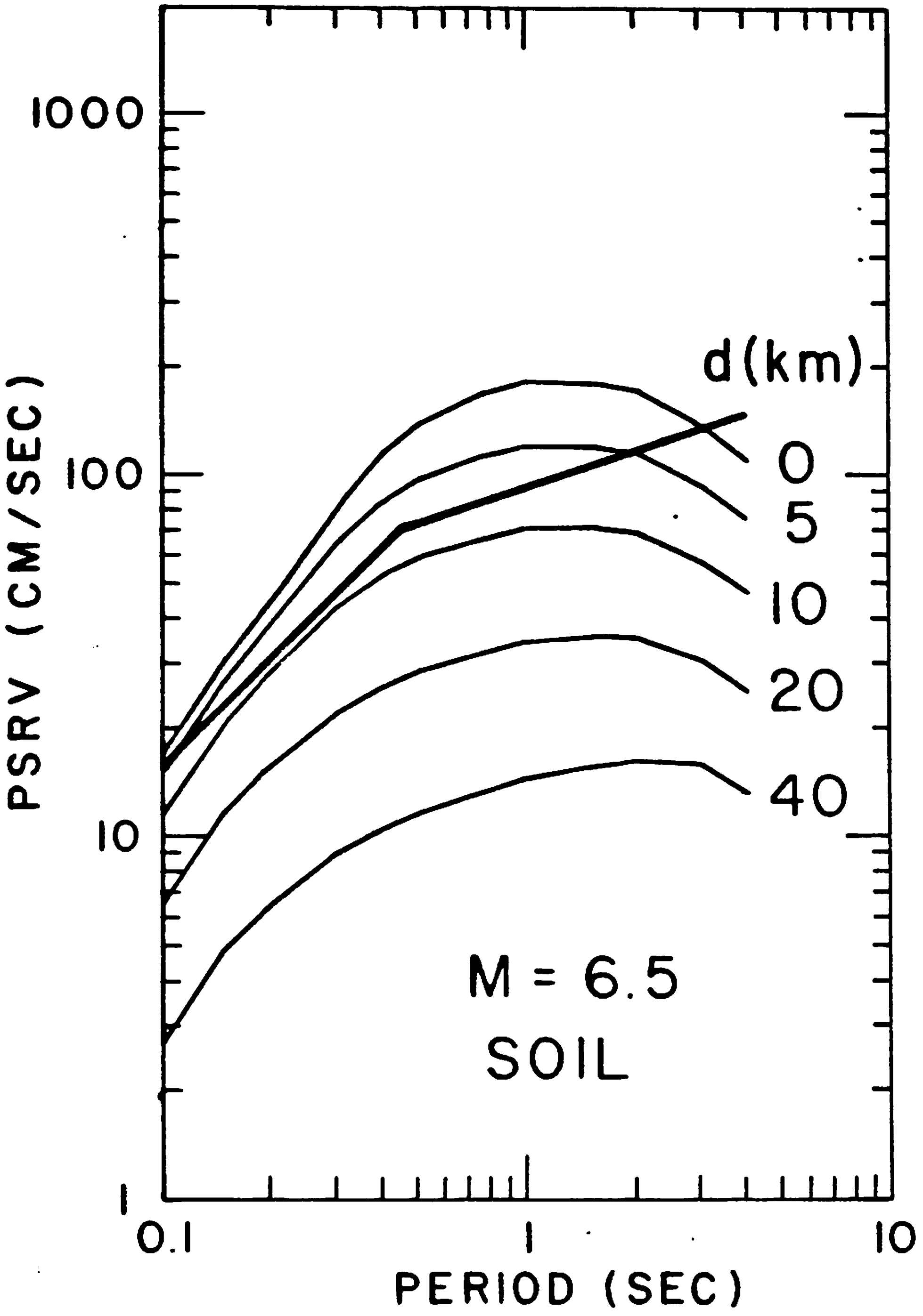

Fig. 7 Predicted pseudo-velocity response spectra for 5 percent damping (light lines) at soil sites for a moment magnitude of 6.5 and d equal to 0, 5, 10, 20, and 40 km compared to the ATC-3 lateral design force coefficient (heavy line) calculated for a response modification factor R of 1.0, for soil type S2, and for A_a and A_v of 0.4. Predicted spectra correspond to the larger of two horizontal components.

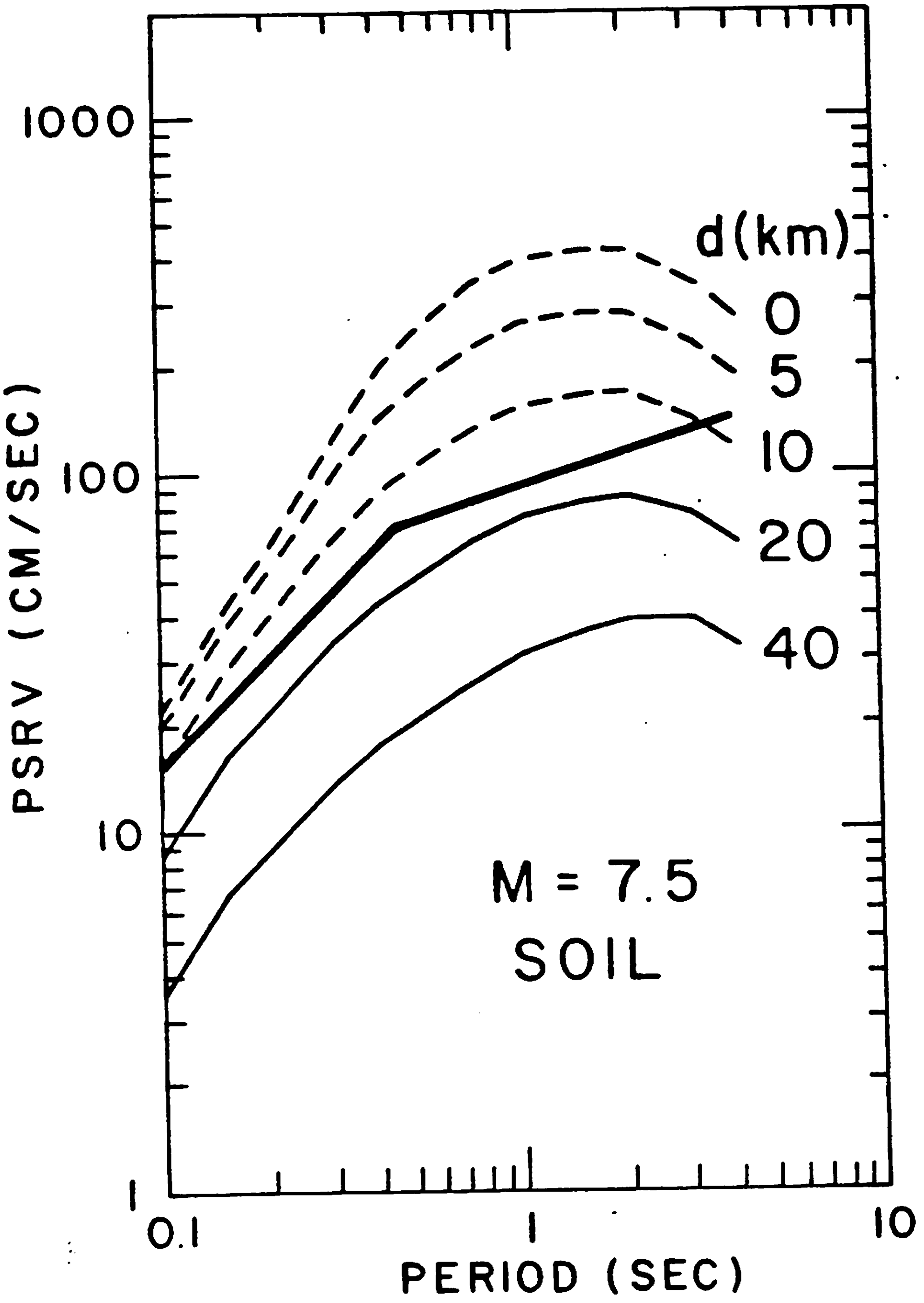

Fig. 8 Predicted pseudo-velocity response spectra for 5 percent damping (light lines) at soil sites for a moment magnitude of 7.5 and d equal to 0, 5, 10, 20, and 40 km compared to the ATC-3 lateral design force coefficient (heavy line) calculated for a response modification factor R of 1.0, for soil type S2, and for A_a and A_v of 0.4. Predicted spectra correspond to the larger of two horizontal components. Curves are dashed where not constrained by data.