Ground motion characteristics and engineering implications of the 1988 Saguenay, Quebec earthquake

N. Naumoski[I], A.C. Heidebrecht[II], and J. Wang[III]

ABSTRACT

An analysis is performed on 31 horizontal components recorded at rock sites during the earthquake which occurred in the Saguenay region of the province of Quebec, Canada, on November 25, 1988. The peak ground motions, response spectra, and base shear coefficients are analyzed statistically. The results are compared with those from other studies and with equivalent parameters in the National Building Code of Canada. It is found that the Saguenay earthquake has produced substantially larger peak ground motions and response spectra than those predicted from other studies. The base shear coefficients for low period structures exceed those from the code provisions.

INTRODUCTION

On November 25, 1988, an earthquake of magnitude M_s=5.7 occurred in the Saguenay region of the province of Quebec, Canada. The earthquake caused some damage in the sparsely populated epicentral region, caused power outages more regionally, and was felt over an extremely large area, as far south as New York City and as far west as Toronto, Ontario. This earthquake was the most significant earthquake in over fifty years in eastern North America (ENA). It was also the first earthquake of significant magnitude whose resulting ground motions were well recorded at large epicentral distances.

Due to lack of data from strong earthquakes in eastern Canada, the predictions of earthquake ground motions in this region have been based on data from western North America (WNA) (Hasegawa et al. 1981), or stochastic prediction techniques have been developed based on theoretical models (Atkinson and Boore 1990). Similarly, the response related parameters, such as the base shear coef-

---

I Research Engineer, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7.

II Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7.

III Graduate Student, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7.

ficients incorporated in the National Building Code of Canada 1990 (NBCC 1990) are defined based on strong earthquake records from other regions in the world. The Saguenay earthquake records provide valuable information for verification and updating the present prediction techniques of earthquake ground motions in eastern Canada, and for evaluation of the base shear coefficients used in NBCC 1990.

In this study, the peak ground motions, response spectra, and base shear coefficients of the Saguenay earthquake are analyzed statistically. The peak ground motions and the response spectra are compared with the predictions for ENA and WNA. The base shear coefficients are compared with those specified in NBCC 1990.

GROUND MOTION DATA

The motions at rock sites during the Saguenay earthquake were recorded by ten accelerographs from the Eastern Canada Strong Motion Seismograph Network (Munro and Weichert 1989), at epicentral distances between 43 and 177 km. In addition, six rock records at distances between 200 and 525 km were obtained by the National Center for Earthquake Engineering Research (NCEER) (Friberg et al. 1988). In this study, the 31 horizontal components from these records are analyzed.

The peak values of the ground motion range from 0.13 to 15.6%g for acceleration, and from 0.1 to 4.65 cm/sec for velocity. The records are characterized with high peak acceleration, a, to peak velocity, v, (a/v) ratios. With exception of one component which has a/v=1.04, the a/v ratios of the other components range from 1.26 to 9.68. As is expected, the a/v ratios tend to decrease with increasing epicentral distance. However, it is surprising to get high a/v ratios (greater than 1.26) at very long epicentral distances (300 to 500 km), which is the case with the NCEER records. Because these are the first data recorded far from the epicentre of an earthquake in eastern North America, it is not clear whether the high a/v ratios at very long epicentral distances are due to the seismo-tectonic characteristics of this region, or some other factors.

ATTENUATION MODEL FOR PEAK GROUND MOTIONS AND RESPONSE SPECTRA

The attenuation functions of the horizontal peak ground acceleration, peak ground velocity and spectral velocity in terms of the epicentral distance were determined using least-square regression analysis. The following form of equation was used

$$\log y = b_1 + b_2 \log R + b_3 R \quad (1)$$

in which y is the peak ground motion variable being defined, R is epicentral distance, and b_1, b_2 and b_3 are coefficients determined by the regression analysis. Equation 1 represents a simplified version of the attenuation model proposed by Joyner and Boore (1988). In the original model, the coefficient b_1 is magnitude dependent and it controls the level of the attenuation curves for different magnitudes. In this study, the data set used is from a single earthquake and b_1 is assumed to be magnitude independent. Concerning the coefficients b_2 and b_3, the Joyner and Boore (1988) approach is followed for determining their values, e.g. only one of these two coefficients is determined by the regression analysis. Usually b_2 is set equal to -1, and the regression analysis is carried out to determine b_1 and b_3. In the case when a positive value is obtained for b_3, it is set to zero, and the coefficients b_1 and b_2 are determined by the regression analysis.

PEAK GROUND MOTIONS

The attenuation functions for mean horizontal peak ground acceleration, a, and peak ground velocity, v, determined by the regression analysis have the following form

$$\log a = 4.064 - \log R - 0.00215\,R; \quad \sigma_{\log a} = 0.231 \qquad (2)$$

$$\log v = 2.414 - \log R - 0.00101\,R; \quad \sigma_{\log v} = 0.299 \qquad (3)$$

where the acceleration is in cm/sec^2, the velocity is in cm/sec, and the epicentral distance, R, is in km.

Figures 1 and 2 show some of the features of the acceleration attenuation. Figure 1 shows the distribution of the acceleration data on which the attenuation curves (mean, and mean +/- 1 standard deviation) are superimposed. As can be seen, the dispersion of the data around the mean curve is relatively small. Figure 2 shows a comparison between the mean attenuation curve for peak ground acceleration for the Saguenay earthquake and those obtained by Hasegawa et al. (1981) for eastern Canada (EC), Atkinson and Boore (1990) for ENA, and Joyner and Boore (1988) for WNA, all of which are developed for rock. The curves from these studies are computed for the magnitude of the Saguenay earthquake of 5.7. The comparison with the Hasegawa et al. (1981) curve (referred to as Hasegawa curve in the further discussion) is of special interest because the same attenuation relation has been used for developing the probabilistic seismic zoning maps for eastern Canada. As is shown, at epicentral distances less than 300 km, the Saguenay earthquake produced larger accelerations than those predicted by Hasegawa equation. At short epicentral distances, below 100 km, the Saguenay earthquake curve is about 2 times higher than the Hasegawa curve. For long epicentral distances, beyond 300 km, the Saguenay earthquake peak ground accelerations are substantially lower than those predicted by the Hasegawa attenuation relation. Concerning the Atkinson and Boore (1990) curve and the Joyner and Boore (1988) curve, both are similar in shape with that of the Saguenay earthquake, but the predictions based on these curves are very low in comparison with the accelerations obtained during the Saguenay earthquake.

The results for the horizontal peak ground velocity are shown in Figs. 3 and 4. As can be seen from Fig. 3, the dispersion of the velocity data around the mean curve is somewhat larger than that for the acceleration data, which leads to a larger standard deviation (see Eq. 3). Figure 4 shows a comparison between the attenuation relation for the mean ground velocity from the Saguenay earthquake and those from the foregoing studies. In terms of the Hasegawa prediction, the Saguenay earthquake has produced larger velocities for a wide range of epicentral distances, below 500 km. At short epicentral distances, below 100 km, the mean velocities from the Saguenay earthquake are about 2.5 times larger than those predicted by Hasegawa. The Atkinson and Boore (1990) and the Joyner and Boore (1988) curves are substantially below the Saguenay earthquake curve for all epicentral distances.

Attenuation of Response Spectra

To investigate the characteristics of the ground motions during the Saguenay earthquake in terms of the response of single-degree-of-freedom systems at different epicentral distances, the attenuation relations for 5% damped pseudovelocity response spectra were determined using regression analysis. The analysis was performed for 14 periods, between 0.01 and 4.0 sec, using the attenuation model given in Eq. 1. The coefficients and standard deviations obtained from the regression analysis are listed in Table 1. These enable one to determine the Saguenay earthquake spectra at any epicentral distance.

Table 1. Regression coefficients and standard deviations for pseudovelocity response spectra, 5% damping

$(\log S_v = b_1 + b_2 \log R + b_3 R)^*$

Period(s)	b_1	b_2	b_3	$\sigma_{\log Sv}$
0.01	1.300	-1	-0.213E-02	0.219
0.02	1.712	-1	-0.242E-02	0.217
0.03	1.951	-1	-0.251E-02	0.208
0.05	2.207	-1	-0.231E-02	0.205
0.08	2.477	-1	-0.228E-02	0.211
0.1	2.573	-1	-0.226E-02	0.251
0.2	2.780	-1	-0.175E-02	0.331
0.3	2.656	-1	-0.920E-03	0.301
0.5	2.529	-1	-0.466E-03	0.287
0.8	2.385	-1	-0.138E-03	0.334
1.0	2.250	-1	-0.557E-05	0.369
2.0	1.097	-0.620	0.	0.342
3.0	0.518	-0.452	0.	0.320
4.0	0.862	-0.696	0.	0.303

$^*S_v$ = pseudovelocity in cm/sec; R = epicentral distance in km.

Because of the limitation in the length of this paper, the shapes of the spectra in terms of the epicentral distance are not shown here. It should be mentioned, that the spectra are characterized with relatively low predominant periods which range from 0.2 sec at epicentral distance of 50 km to 0.6 sec at 400 km.

Figure 5 shows a comparison between the Saguenay earthquake spectrum at epicentral distance of 100 km and the spectra for rock sites predicted by Atkinson and Boore (1990) for ENA and by Joyner and Boore (1988) for WNA. As can be seen, the Saguenay earthquake spectrum is much higher than the predicted spectra. The predominant period of the ground motion is about 0.25 sec, and it is substantially lower than the predominant periods of the Atkinson and Boore (1990) spectrum, which range from 0.5 to 1.0 sec. Concerning the Joyner and Boore (1988) spectrum, it has a shape which is substantially different than that of the other spectra.

Spectral Amplifications

The codes for seismic design usually define the design spectra by spectral amplification factors in terms of the peak ground motions. These factors are commonly specified at mean + 1 standard deviation (M+1SD) level in order to ensure that there is a relatively small probability that the response will be above the specified design level.

In this study, the amplifications of the Saguenay earthquake spectra in terms of the peak ground acceleration and velocity are examined. To assess the influence of the epicentral distance on the spectral amplification, the spectra are analyzed in three groups, which correspond to the following ranges of epicentral distances: 40 to 100 km, 100 to 200 km and 325 to 525 km. The epicentral distances within these ranges will be conditionally referred to as short, intermediate and long epicentral distances. The first group comprises the spectra from 8 components, the second group from 13 components, and the third group from 10 components. The response spectra from each group are scaled to a peak ground acceleration of 1g, and to a peak ground velocity of 1m/sec. The M+1SD of the spectra from the acceleration scaling are shown in Fig. 6, and those from the velocity scaling in Fig. 7.

Figure 6 shows that the maximum amplification of the spectra in terms of the peak ground acceleration is about 3.3, in the period range between 0.1 and 0.3 sec. It is associated with the spectra from intermediate and long epicentral distance range. The spectrum from the short epicentral distance range shows maximum amplification of 2.5 at very short periods, around 0.04 sec. This is due to the significant presence of such short period components in the records at short epicentral distances. Concerning the velocity amplification of the spectra, Fig. 7 shows that the spectra from the three ranges of epicentral distances have the same maximum amplification of about 3. It should be noted that both the acceleration and velocity amplification of the Saguenay earthquake spectra of 3.3 and 3.0 respectively are larger than those suggested by Newmark and Hall (1982) (2.71 for acceleration amplification and 2.3 for velocity amplification), which with a slight modifications are accepted in various codes for aseismic design.

BASE SHEAR COEFFICIENTS

The unit velocity base shear coefficients were calculated for each component time history for uniform frame and wall-type structures. Simple continuum models of frame and wall structures were used. The response analysis was performed using time history superposition method, for five modes and 5% modal damping. The base shear coefficients were analyzed statistically for three groups of records obtained at different ranges of epicentral distances (short, intermediate and long epicentral distance range, as defined in the previous section). For each group, the M+1SD level of the base shear coefficients were determined. In this paper, the results are presented only for frame structures because they are larger than those for wall structures for fundamental periods below about 0.5 sec.

Figure 8 shows the M+1SD level of the unit velocity base shear coefficient spectra for the three groups of records, for frame structures with fundamental periods between 0.01 and 4.0 sec. Because the Saguenay records have high a/v ratios, the base shear coefficients are compared with that specified in NBCC 1990 for regions where the zonal acceleration, Z_a, is larger than the zonal velocity, Z_v ($Z_a>Z_v$). As shown in Fig. 8, the base shear coefficients for the records from the short and intermediate epicentral distance range exceed significantly the $Z_a>Z_v$ branch of the NBCC 1990 base shear coefficient, for periods below 0.3 sec. The base shear coefficients for the records obtained at long epicentral distances are slightly higher than that in NBCC 1990 for periods between 0.3 and 0.9 sec.

The features of the unit velocity base shear coefficient spectra for the three groups of records are related to the a/v ratios of the records from each group. For illustration, the mean a/v values of the records from the short, intermediate and long epicentral distance range are 5.5, 2.8 and 1.6 respectively. In terms of the Canadian seismic zoning maps, the largest values of a/v are in the neighbourhood of 2. Heidebrecht and Lu (1987) have shown that even for a/v=2 the base shear coefficient in the code underestimates those for short period frame structures. Taking into account that the a/v ratios of the Saguenay earthquake records from the short and intermediate epicentral distance range are larger than 2, it is obvious why the base shear coefficients for these records are higher than the comparable values in NBCC 1990.

SUMMARY

The analysis and results presented in this paper show that the ground motion during the Saguenay earthquake is characterized by very high peak ground motions and response spectra. It is found that the peak ground accelerations, peak ground velocities and response spectra are significantly larger, for a wide range of epicentral distances, than those from the prediction relations. The prediction relations for eastern Canada should be updated to account for the Saguenay earthquake characteristics.

The effects of the Saguenay earthquake on the response of multi-degree-of-freedom structures is presented in terms of base shear coefficients for frame structures. It is shown that the unit velocity base shear coefficients of the records at distances below 200 km substantially exceed that specified in NBCC 1990 for $Z_a>Z_v$. This is due to the very high a/v ratios of these records. Taking into account that the same observations have also been made in other studies for earthquake records with a/v>2, the base shear coefficient in NBCC 1990 for $Z_a>Z_v$ should be revised to recognize the effects of such earthquake motions.

REFERENCES

Associate Committee on the National Building Code 1990. National Building Code of Canada. National Research Council of Canada, Ottawa, Ontario, Canada.

Atkinson, G.M. and Boore, D.M. 1990. Recent trends in ground motion and spectral response relations for North America. Resp. Spectra, 6, 15-35.

Friberg, P., Rusby, R., Dentrichia, D., Johnson, D., Jacob, K. and Simpson, D. 1988. The M=6 Chicoutimi earthquake of November 25, 1988, in the province of Quebec, Canada. Preliminary NCEER strong motion data report, Lamont-Doherty Geological Observatory of Columbia University, Palisades, N.Y.

Hasegawa, H.S., Basham, P.W. and Berry, M.J. 1981. Attenuation relations for strong seismic ground motion in Canada. Bull. Seism. Soc. Am., 71(6) 1943-1962.

Heidebrecht, A.C. and Lu C.Y. 1987. Evaluation of the seismic response factor introduced in the 1985 edition of the National Building Code of Canada. Can.

J. Civ. Eng., 15, 382-388.
Joyner, W.B. and Boore, D.M. 1988. Measurements, characterization, and prediction of strong ground motion. Proc. ASCE Conf. Soil Dynamics, Geot. Spec. Publ., 20, 43-102, Park City, Utah.
Munro, P.S. and Weichert, D. 1989. The Saguenay earthquake of November 25, 1988 - Processed strong motion records. Earth Phys. Branch Open-file Rpt. 1966.
Newmark, N.M. and Hall, W.J. 1982. Earthquake spectra and design. Monograph series, EERI, Berkeley, California.

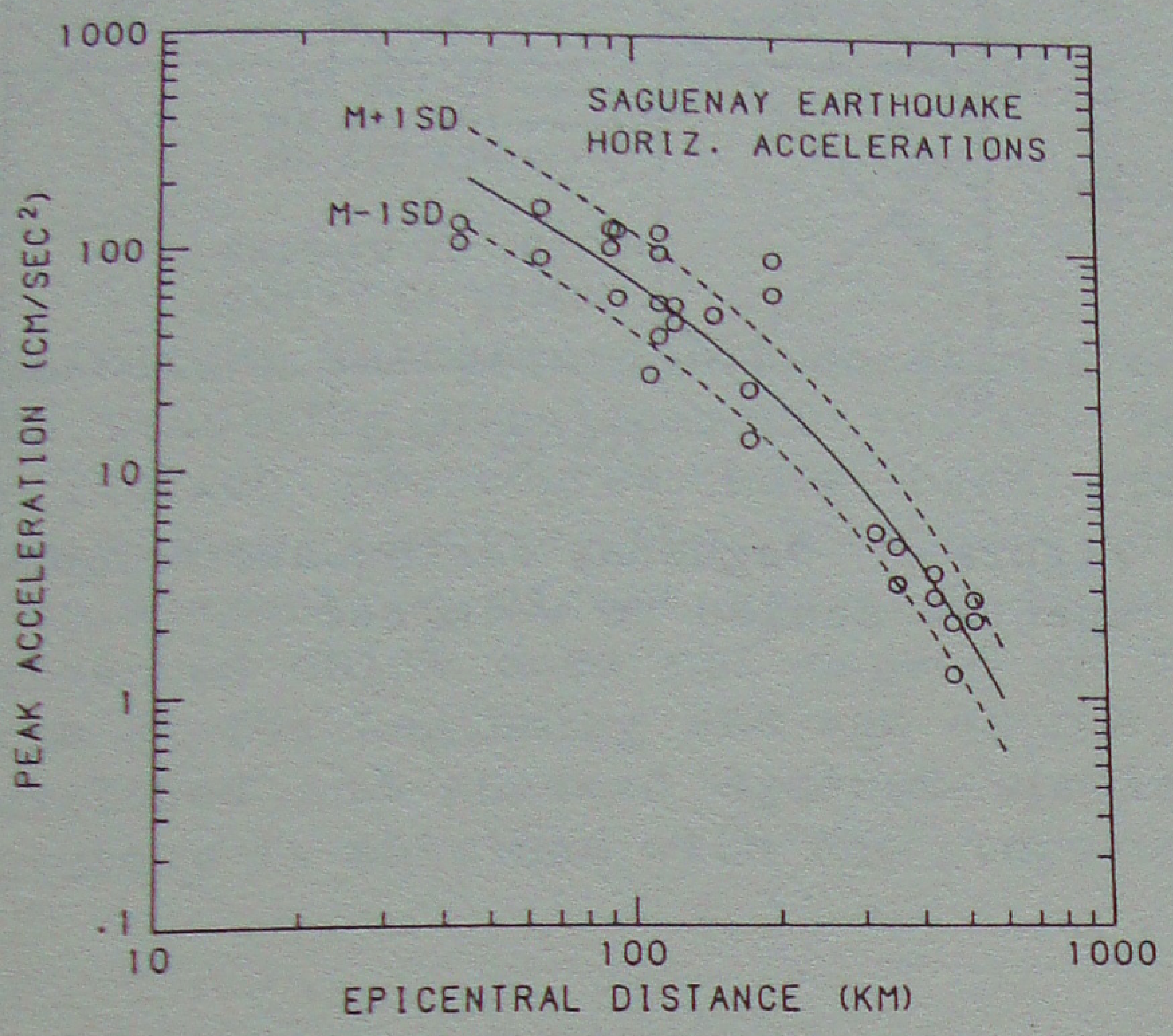

Figure 1. Peak acceleration from the Saguenay earthquake

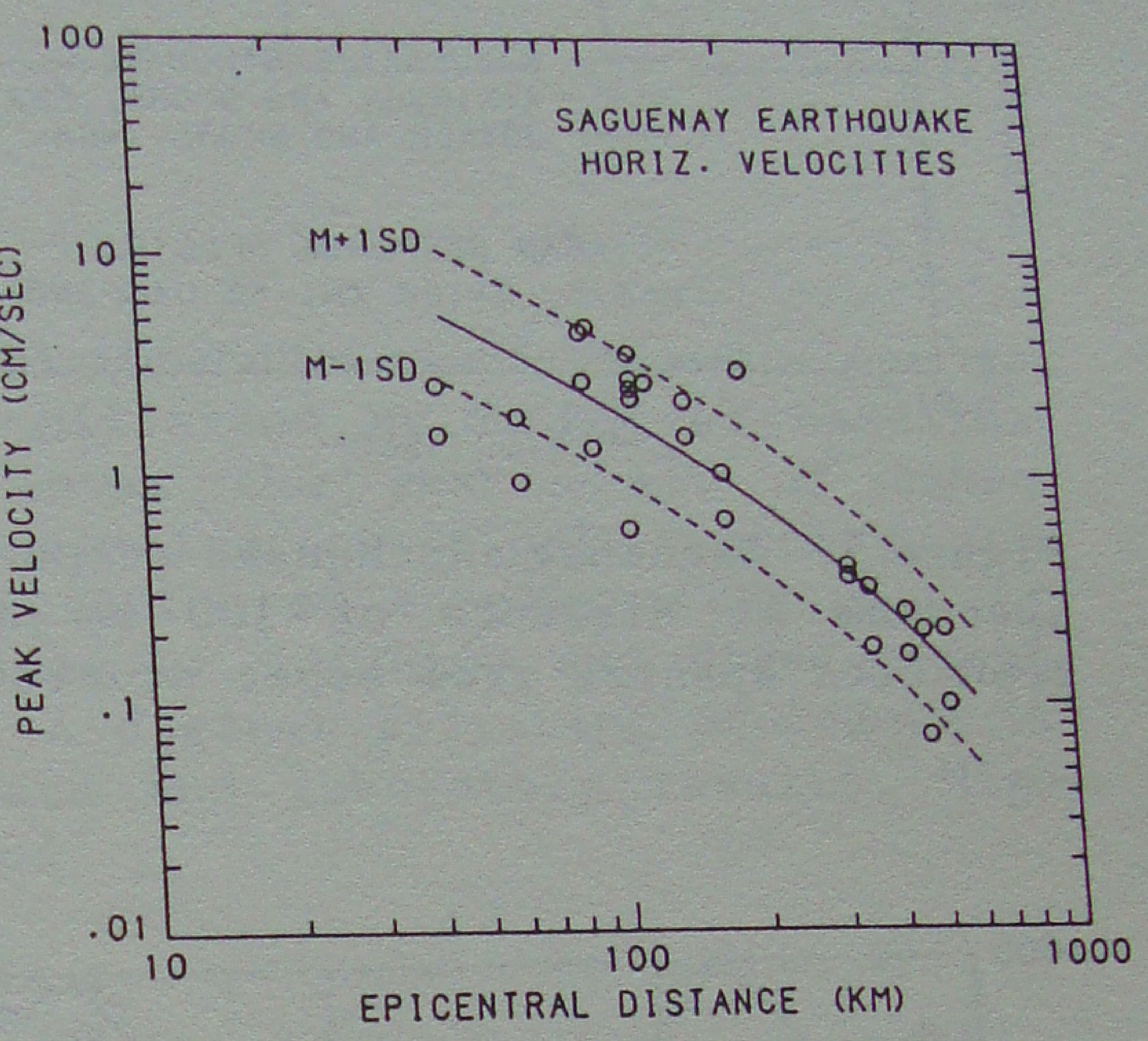

Figure 3. Peak velocities from the Saguenay earthquake

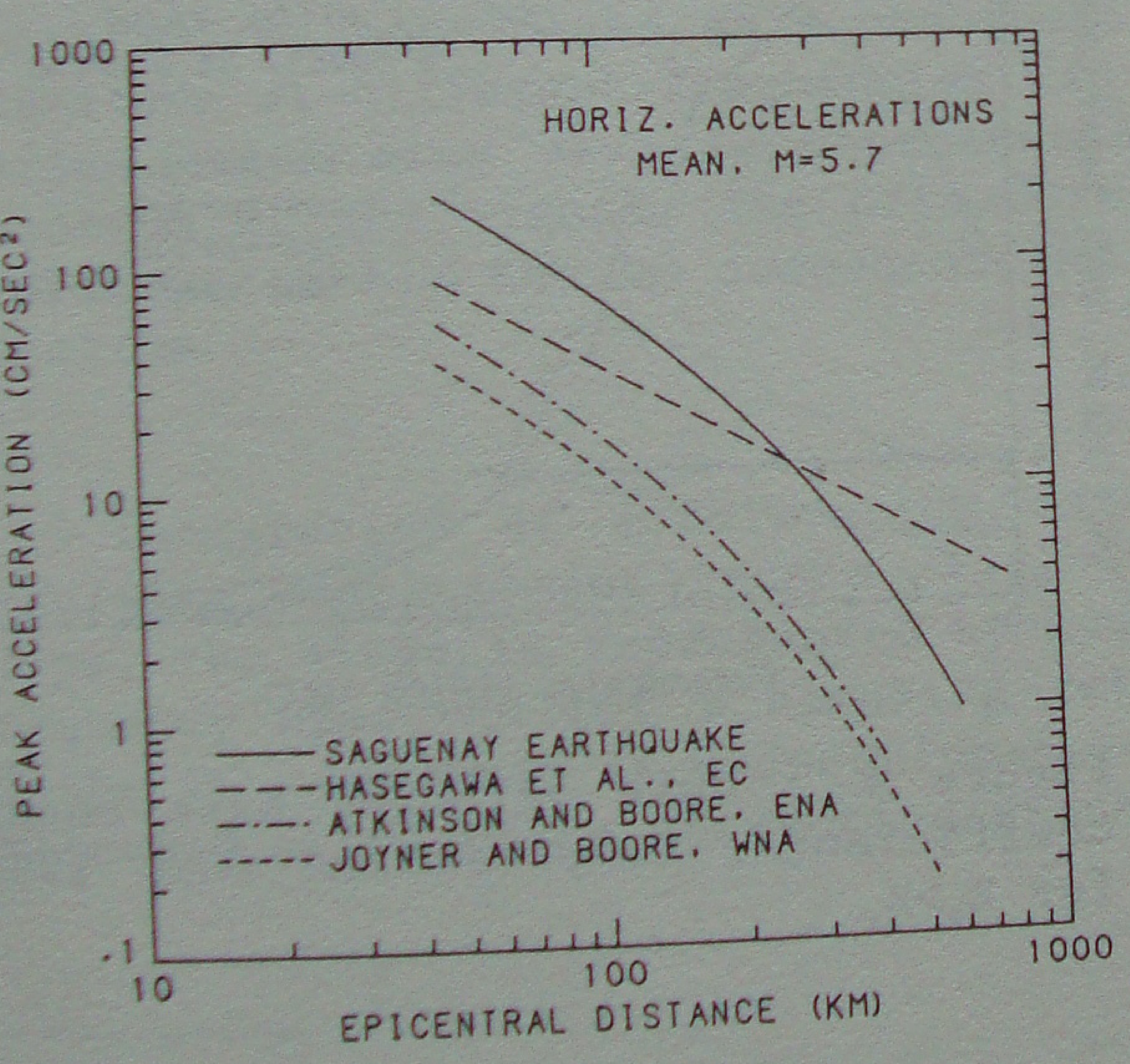

Figure 2. Attenuation curve for the Saguenay earthquake peak ground acceleration and predictions from other studies

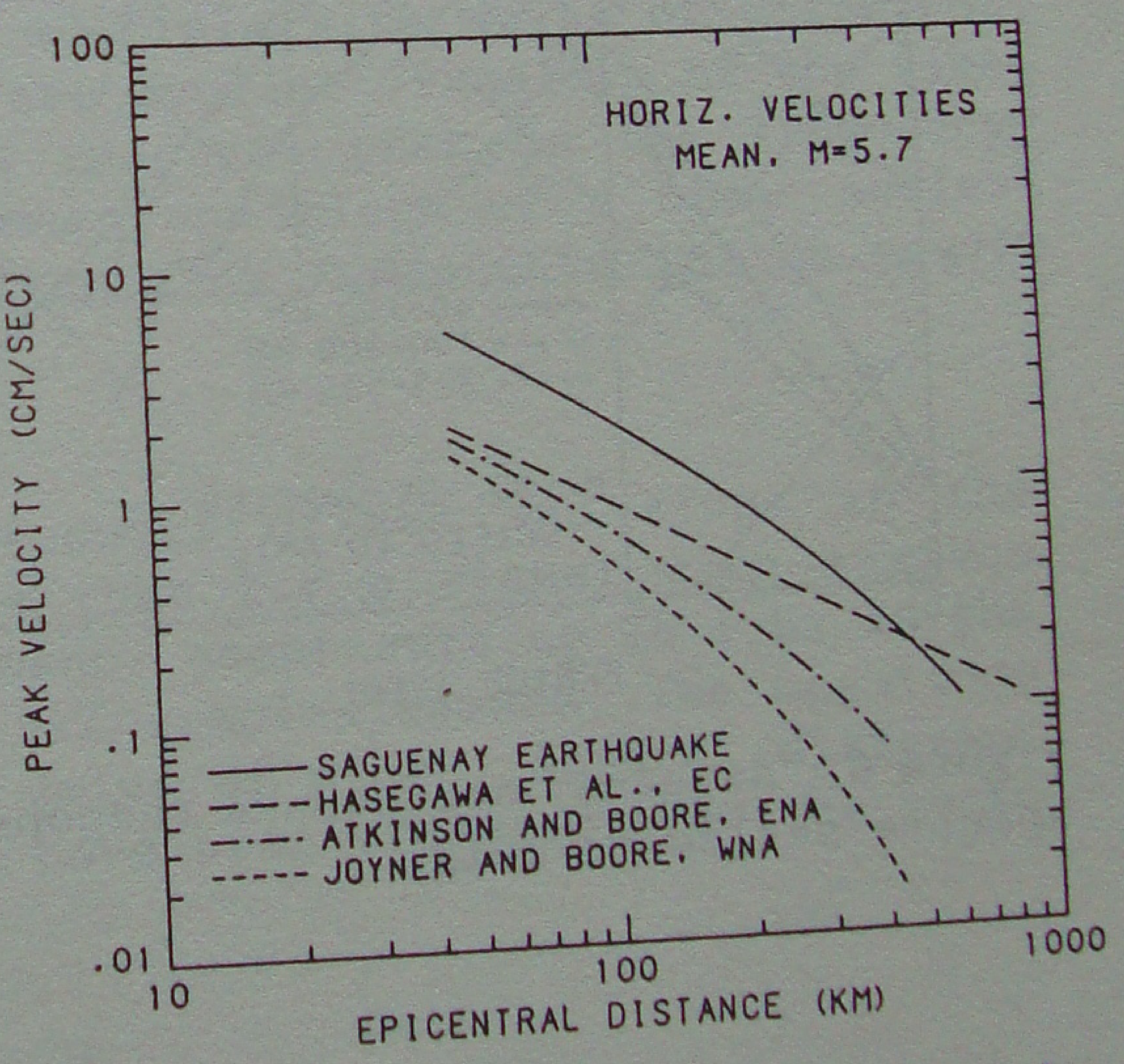

Figure 4. Attenuation curve for the Saguenay earthquake peak ground velocity and predictions from other studies

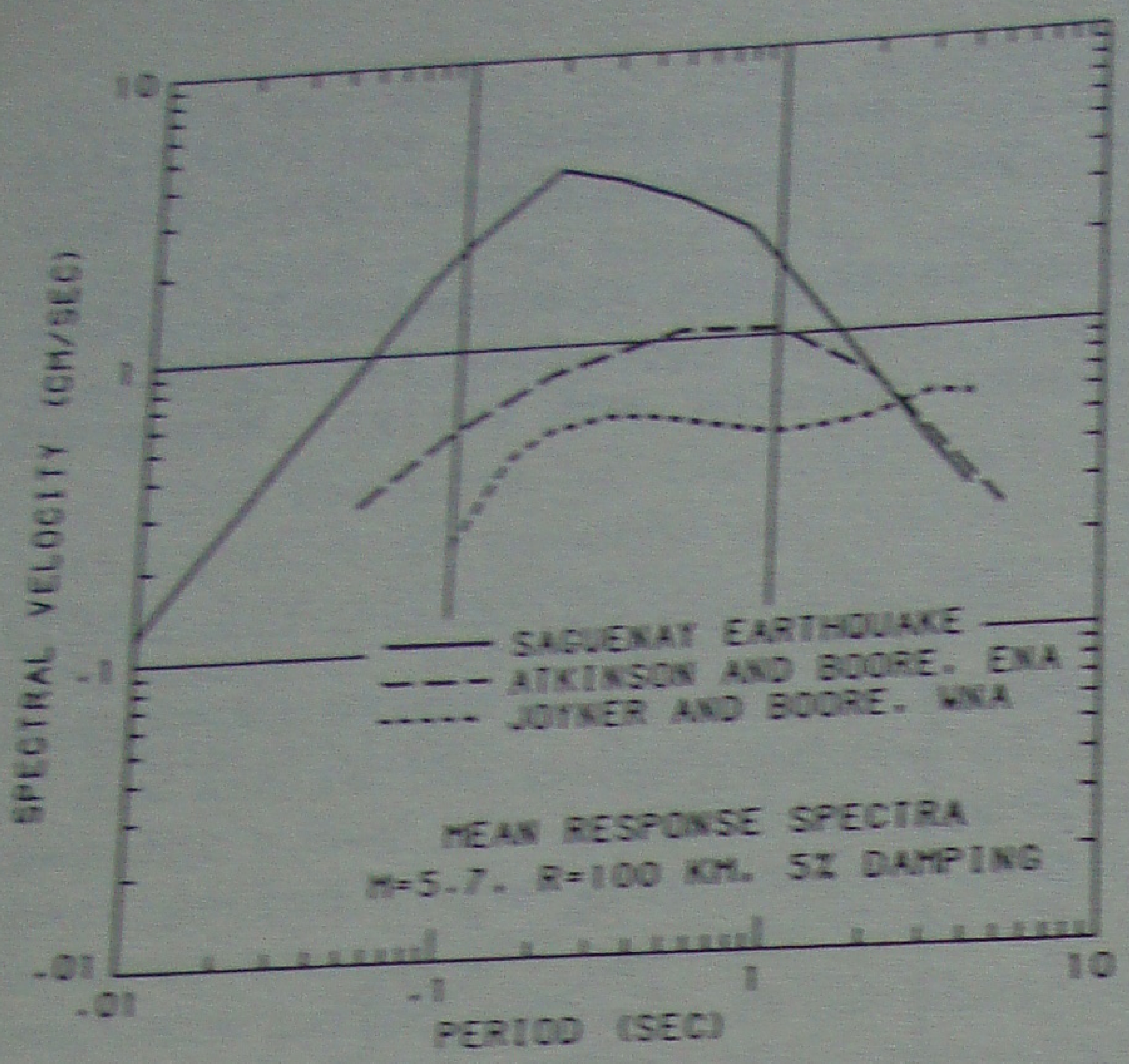

Figure 5. Saguenay earthquake response spectrum at distance of 100 km and predicted spectra from other studies

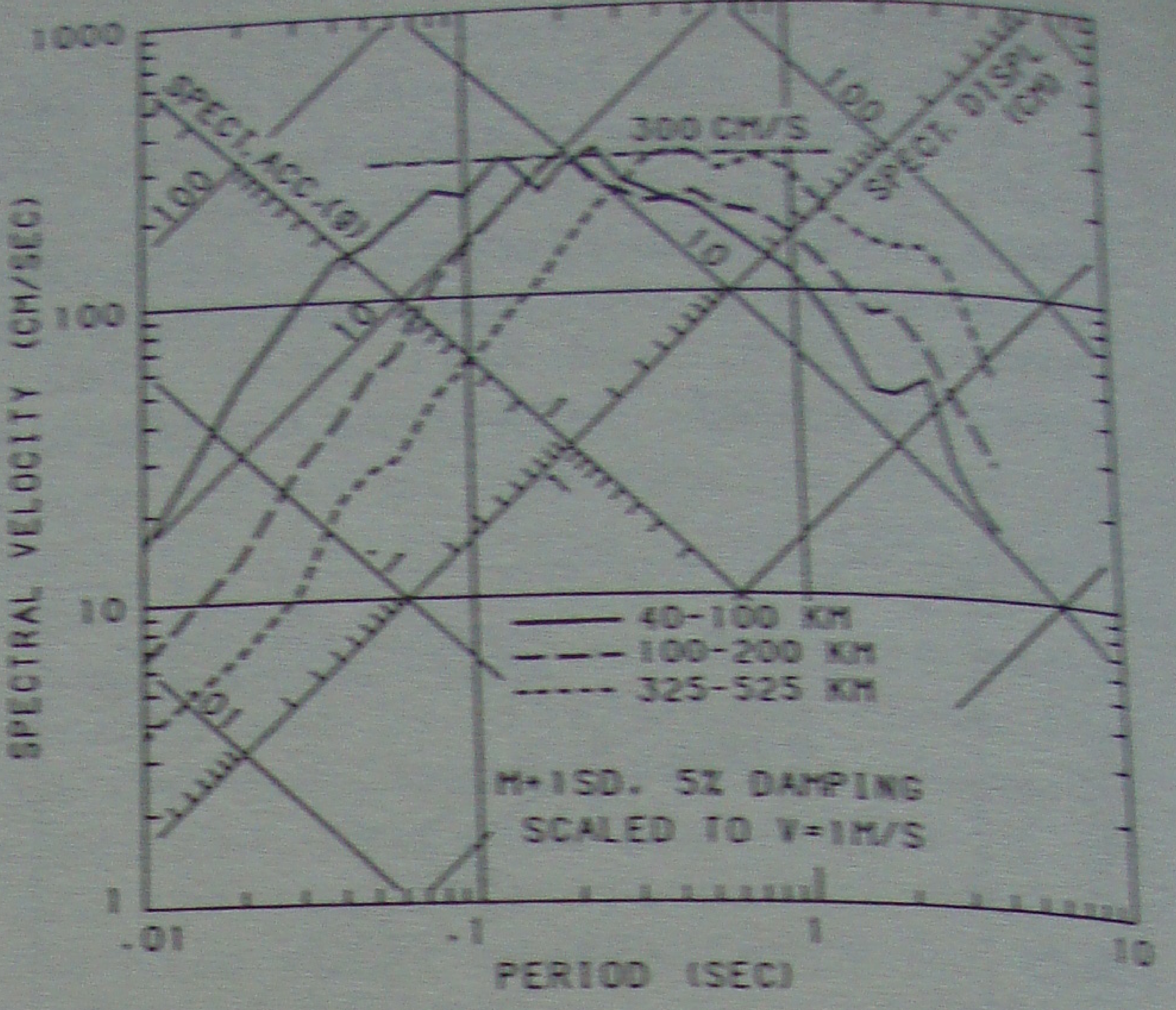

Figure 7. Saguenay earthquake response spectra scaled to v=1m/sec

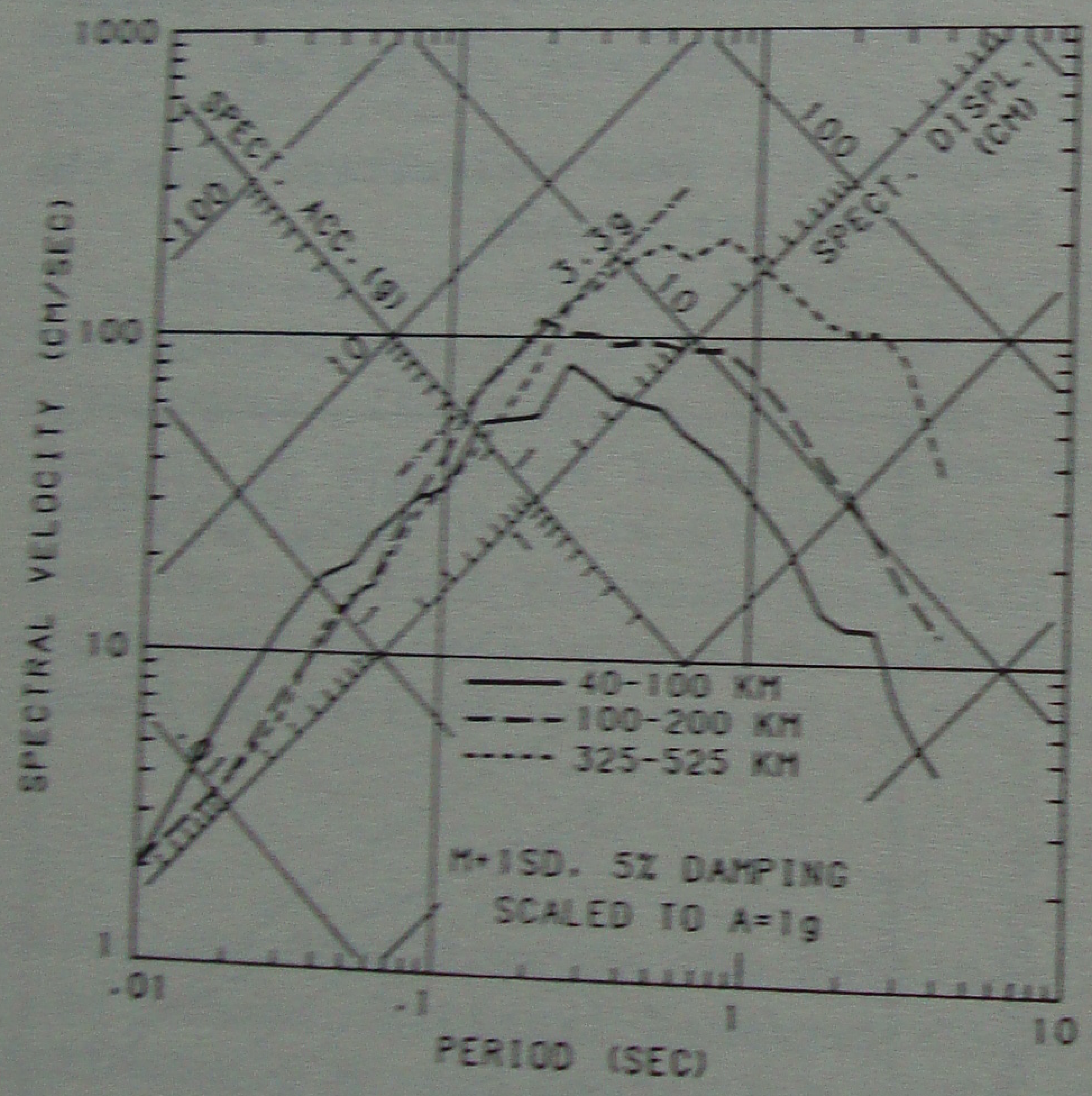

Figure 6. Saguenay earthquake response spectra scaled to a=1g

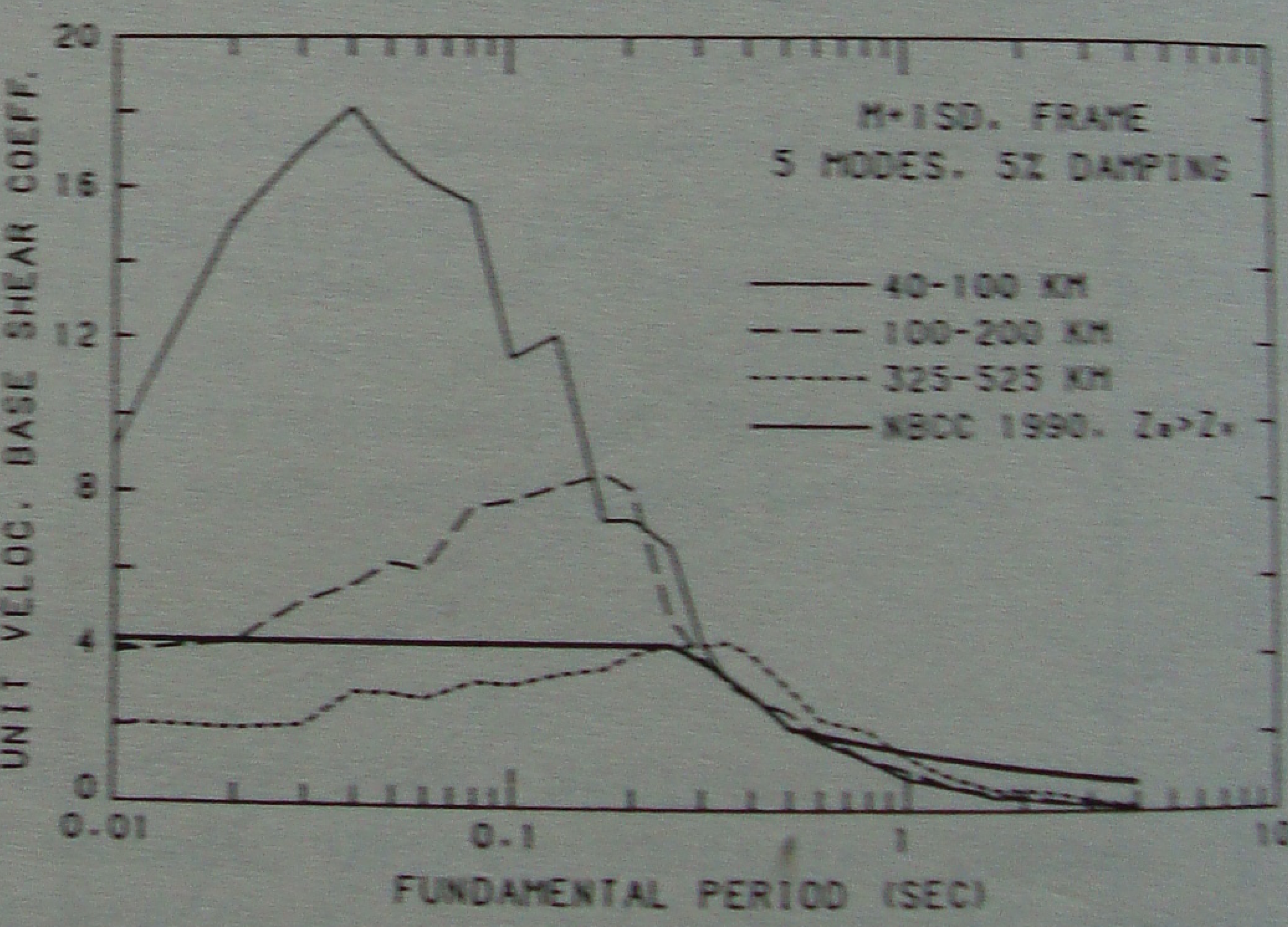

Figure 8. Unit velocity base shear coefficients, computed and NBCC 1990 for $Z_a > Z_v$