5th Canadian Conf. Earthquake Engineering / Ottawa / 1987 / 5ème Conf. Canadienne Génie Sismique

Ductility demand on structures designed based on NBCC 1985 base shear specification

T.J.Zhu, W.K.Tso & A.C.Heidebrecht
McMaster University, Hamilton, Ontario, Canada

ABSTRACT: A statistical analysis based on three sets of earthquake records is performed to investigate the significance of peak ground acceleration to velocity ratio (a/v) on the displacement ductility demand of simple inelastic systems. The yield strength of the systems is specified from the base shear formula in the 1985 National Building Code of Canada (NBCC 1985) and that in NBCC 1980 respectively. In the former case, seismic design forces are specified based on peak ground velocity and a/v ratio whereas the latter case represents the common practice of specifying seismic design forces based on a single peak site acceleration. A comparison of the statistical results between the two methods shows that the a/v ratio of ground motion has a significant effect on the displacement ductility demand and the base shear provisions in NBCC 1985 provide an effective way to incorporate the a/v ratio into design base shear specification.

1 INTRODUCTION

One of the most important steps in seismic design of buildings is the proper representation of design earthquake inputs. As a common approach in current seismic design practice, the design earthquake inputs are characterized by smoothed design response spectra. In many seismic codes and design standards, it has been assumed that one design spectral shape would be sufficient to describe design earthquakes for seismic design. The spectral shape is normally based on the standard design spectrum suggested by Newmark and Hall (1973), and in most cases, peak ground acceleration is used to represent the expected severity of earthquake excitation at a given site for scaling purposes. However, as more earthquake records are obtained, especially after the 1971 San Fernando earthquake, it becomes apparent that the use of a single design spectrum shape is inadequate because some of the earthquake ground motions can have response spectra dramatically different from the standard design spectrum. Newmark (1975,1976) observed that structures near an earthquake source may experience short-duration and high-frequency acceleration motions. Bertero et al. (1976,1978) and Mahin and Bertero (1981) indicated that ground motions near the fault rupture may contain severe, long duration acceleration pulses which would result in very high displacement ductility demands for inelastic systems designed based on the standard design spectrum. Hall (1982,1986) noticed the need to use another design spectrum for a distant earthquake source on the basis that ground motions distant from the energy source would generally be of long-period sustained type due to the filtering effect through ground media. Therefore, the standard design spectrum may be representative of strong seismic ground motions at moderate distances from the causative fault, but to allow for ground motions close to or distant from the energy source, additional design spectra may need to be developed on the basis of recorded near-field and far-field earthquake accelerograms.

Seismological studies have indicated that the attenuation of ground motion velocity with distance is generally slower that the attenuation of acceleration. Therefore, the a/v ratio would be high near an earthquake source; and it would be low at large distance from a major earthquake. Ground motions in the former case may be of short-duration, high-frequency, and impulsive type whereas those in the latter case would be of longer-duration and more periodic type. Also, inspection of earthquake records (Zhu (1985)) has revealed that ground motions with a high frequency content in the strong-motion phase would generally correspond to high a/v ratios whereas those containing intense, long duration acceleration pulses would generally be associated with low a/v ratios. Ground motions at moderate distances from the energy source would generally have a broad range of significant frequency content, resulting in intermediate a/v ratios. Therefore, the a/v ratio would provide some information on the frequency characteristics of ground motions in a statistical sense.

In the 1985 edition of the National Building Code of Canada (NBCC 1985) (Associate Committee on the National Building Code 1985), both peak ground velocity and a/v ratio are used to characterize the design seismic ground motion, and the specification of a design base shear is based on these two ground motion parameters. A detailed discussion on the primary features of the seismic loading provisions in NBCC 1985 has been presented by Heidebrecht and Tso (1985). The objectives of this paper are to investigate the significance of ground motion a/v ratio on the displacement ductility demand of simple nonlinear yielding systems and to evaluate the effectiveness of the base shear provisions in NBCC 1985 as an approach to incorporate a/v ratio into design base shear specification.

2 DESIGN STRENGTH SPECIFICATION

To facilitate dynamic analysis and result presentation, only single-degree-of-freedom (SDOF) inelastic systems are considered in the present study. The bilinear force-deformation model with strain-hardening stiffness equal to 3% of the initial elastic stiffness is used to approximate the hysteretic behavior of the systems. The viscous damping for the systems is taken as 2% of critical.

The yield strength of the systems is specified from the base shear formula in NBCC 1980 (Associate Committee on the National Building Code 1980) and that in NBCC 1985 respectively. The base shear provisions in NBCC 1980 represent the common practice of specifying seismic design forces based on a single design spectrum shape scaled by a peak site acceleration whereas those in NBCC 1985 represent an improved method to specify seismic design forces based on peak ground velocity and the a/v ratio of ground motion. A comparison of the statistical results between the two methods of specifying seismic design forces will permit an assessment of the significance of a/v ratio as a parameter to characterize the damage potential of seismic ground motion and the effectiveness of the base shear provisions in NBCC 1985 as an approach to incorporate a/v ratio into design strength specification.

2.1 Design strength specification based on NBCC 1980

In NBCC 1980, the base shear V for a building is specified as

$$V = ASKIFW \tag{1}$$

where A is the zonal acceleration ratio defined as the ratio of zonal peak ground acceleration to the acceleration of gravity, S the seismic response factor, F the foundation factor, and W the weight of all the reactive masses that induce inertia forces in the building. The acceleration ratio A reflects the expected severity of earthquake excitation at a given site and corresponds to a probability of exceedance of 0.01 per annum. It should be noted that this probability level used in seismic risk mapping is not directly related to the probability of exceedance associated with the seismic lateral forces, and the latter is expected to be much lower (Heidebrecht et al. (1983)). Based on the standard design spectrum, the seismic response factor S determines the variation pattern of design base shear with structural period, as shown in Figure 1. The

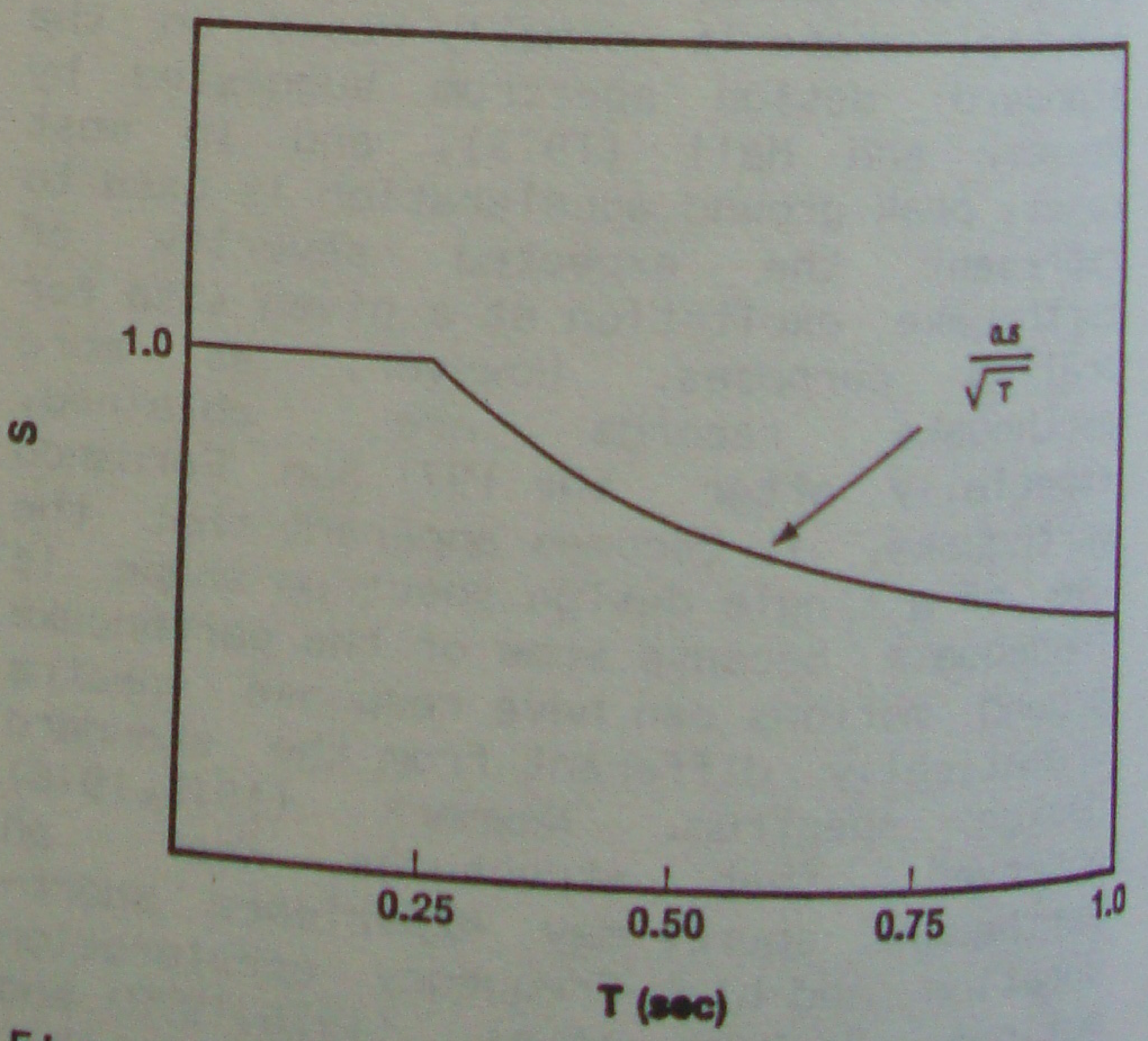

Figure 1. Seismic response factor S in NBCC 1980

structural behavior coefficient K is intended to account for the energy absorption and dissipation capacities of different types of structural systems through inelastic deformation and damping.

In the first part of this study, the yield resistances of the bilinear systems are specified from equation (1). A is taken as 0.08, and all the input ground motions are normalized to a common peak acceleration of 0.2g whose probability level is appropriate to the design forces provided by A=0.08 in the base shear formula. For rock or stiff soil sites (F=1.0) and building structures of normal importance (I=1.0), the design yield strength for a system is given by

$$\begin{aligned} R_y &= 1.5\ V \\ &= 1.5 \times 0.08\ SKW \\ &= 0.12\ SKW \end{aligned} \qquad (2)$$

where 1.5 is the load factor used in design for earthquake loading. The seismic resistance coefficient which is defined as the ratio of the yield strength of the system to its weight, is given by

$$C_y = R_y/W = 0.12\ SK \qquad (3)$$

2.2 Design strength specification based on NBCC 1985

The NBCC 1985 formula for the base shear V is given by

$$V = 0.44\ vS_NKIFW \qquad (4)$$

in which K, I, F, and W have the same meaning as in NBCC 1980; v is the zonal velocity ratio defined as the ratio of zonal peak ground velocity to a velocity of 1 m/s; S_N is a new seismic response factor described graphically in Figure 2. The zonal velocity ratio corresponds to a probability of exceedance of 10% in 50 years which is appropriate to the seismic design forces provided by the base shear formula (Heidebrecht et al. (1983)). It can be noted that the design base shear is directly related to peak ground velocity for structural periods longer than 0.5 sec while the effect of peak ground acceleration on short-period structures is accounted for by using three different levels of seismic response factor for the three different zonal combinations ($Z_a<Z_v$, $Z_a=Z_v$, and $Z_a>Z_v$) corresponding to low, normal, and high a/v ranges.

In the second part of this study, the yield strength of the systems is specified from equation (4). v is taken as 0.2, and all the input ground motions are normalized to a common peak velocity of 0.2 m/s. For F=1.0 and I=1.0, the yield strength for a system is given by

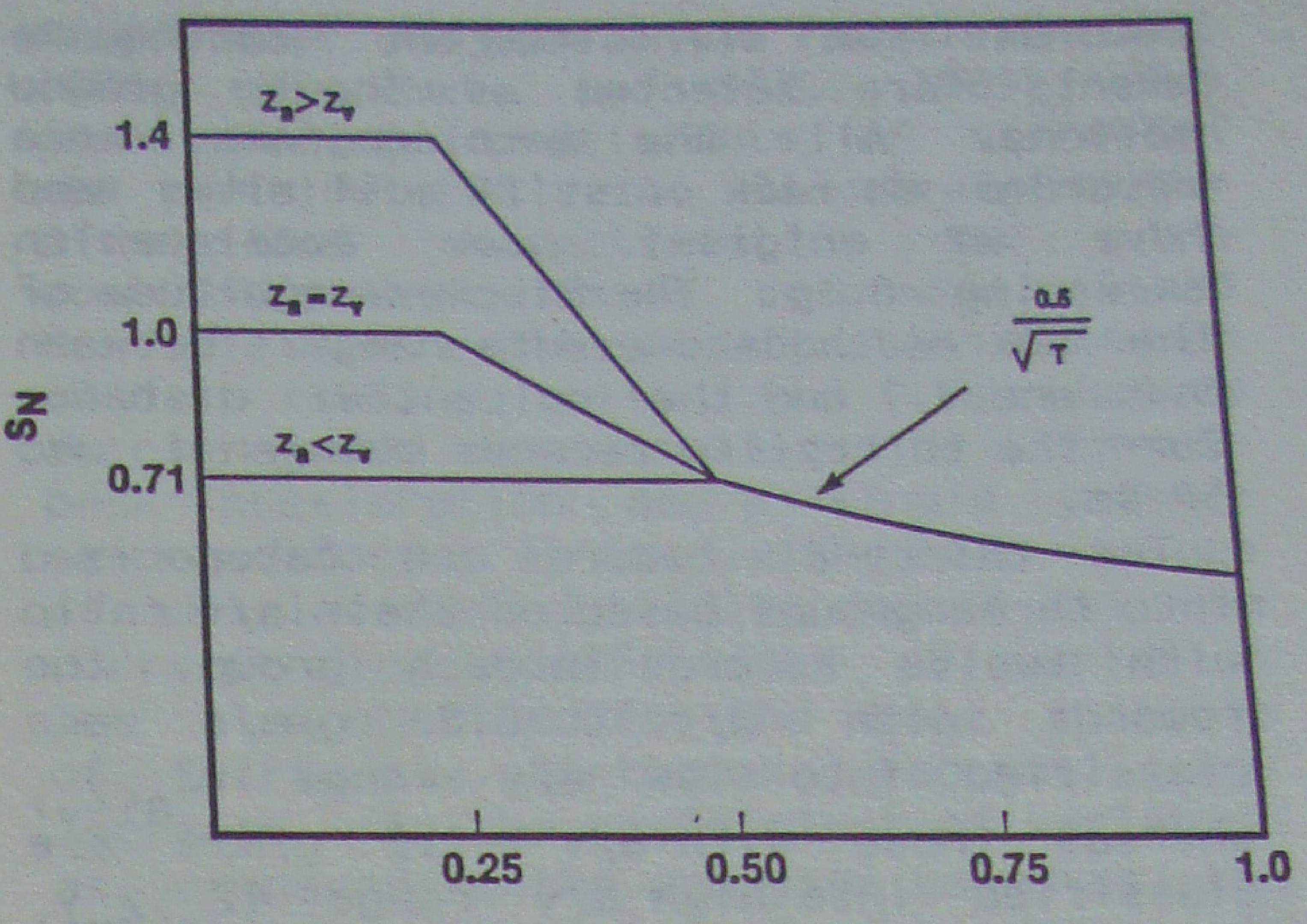

Figure 2. Seismic response factor S_N in NBCC 1985

$$\begin{aligned} R_y &= 1.5\ V \\ &= 1.5 \times 0.44 \times 0.2\ S_NKW \\ &= 0.132\ S_NKW \end{aligned} \qquad (5)$$

in which 1.5 is again the load factor. The corresponding seismic resistance coefficient is given by

$$C_y = R_y/W = 0.132\ S_NK \qquad (6)$$

In both cases of yield strength specification, five different yield strength levels are considered, corresponding to K= 0.7, 1.0, 1.3, 2.0, and 5.0. The first four K values are recommended by both NBCC 1980 and NBCC 1985 for various types of structural systems ranging from complete moment resisting ductile frames (K=0.7) to unreinforced masonary structures (K=2.0). K=5.0 is included because previous study (Heidebrecht, Tso and Cherry (1983)) indicates that buildings designed with this value would be expected to reach the threshold of yielding under earthquake excitation. The initial undamped period of the systems considered varies from 0.1 to 2.0 sec, a period range covering the fundamental periods of most building structures.

3 INPUT GROUND MOTION

A total of thirty-six horizontal components of the western United States records from six different earthquake events are selected as input ground motions. All the accelerograms were recorded on rock or stiff soil sites and have an original peak acceleration exceeding 0.1g. The Ritcher magnitude of the six earthquake events ranges between 5.6 and 7.7 and the epicentral distance for the thirty-six records between 4 and 58 km.

The thirty-six records are categorized into three groups based on their a/v ratio with twelve records in each group. The records with a/v < 0.8 g/m/s are classified into low a/v range ($Z_a<Z_v$) whereas those with a/v > 1.2 g/m/s are classified into high a/v range ($Z_a>Z_v$). The records with 0.8 g/m/s < a/v < 1.2 g/m/s are classified into normal a/v range ($Z_a=Z_v$). The three a/v ranges correspond to the three zonal cases in NBCC 1985. A statistical summary of the a/v ratios for the three sets of earthquake records is presented in Table 1. A detailed list of the earthquake records in the three a/v ranges can be found in the reference by Zhu (1985).

Table 1. Statistical summary of a/v ratios for the three sets of earthquake records

	Low a/v ($Z_a<Z_v$)	Normal a/v ($Z_a=Z_v$)	High a/v ($Z_a>Z_v$)
Range	0.52-0.69	0.88-1.09	1.53-3.26
Mean	0.61	0.99	2.00
COV*	0.08	0.07	0.27

*Coefficient of variation

In order to illustrate the significant frequency content associated with each set of erathquake records, the mean elastic acceleration response spectrum for each set is computed. Shown in Figure 3 are the mean 2% damped elastic acceleration spectra for the three separate sets and the whole ensemble of earthquake records normalized to a common peak acceleration of 0.2g. Superimposed in the same figure are the five seismic resistance coefficients from equation (3) as a function of structural period for the five K values. The product of the weight and

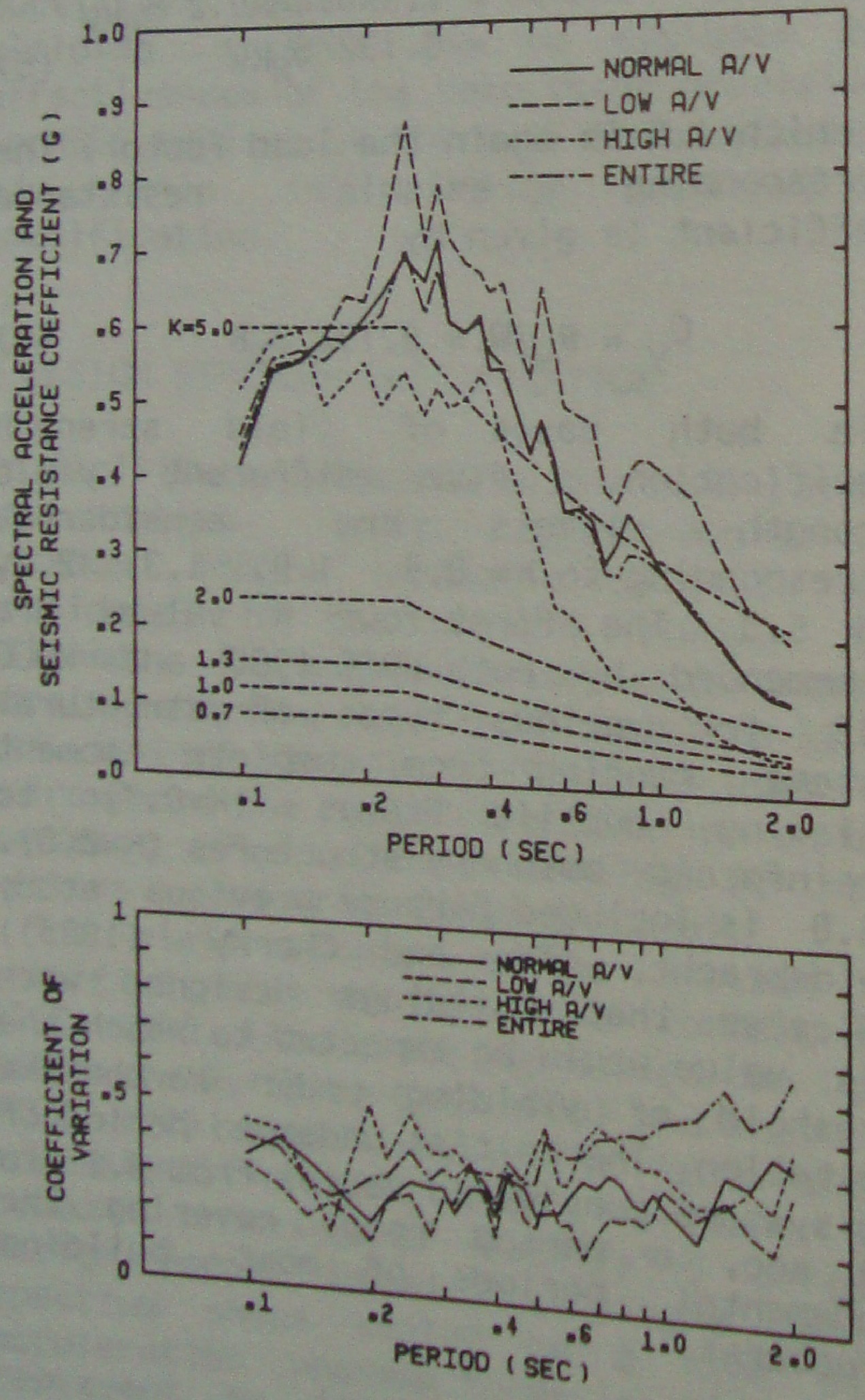

Figure 3. Mean 2% damped elastic acceleration spectra normalized to a peak acceleration of 0.2g and seismic resistance coefficients for A=0.08 in NBCC 1980

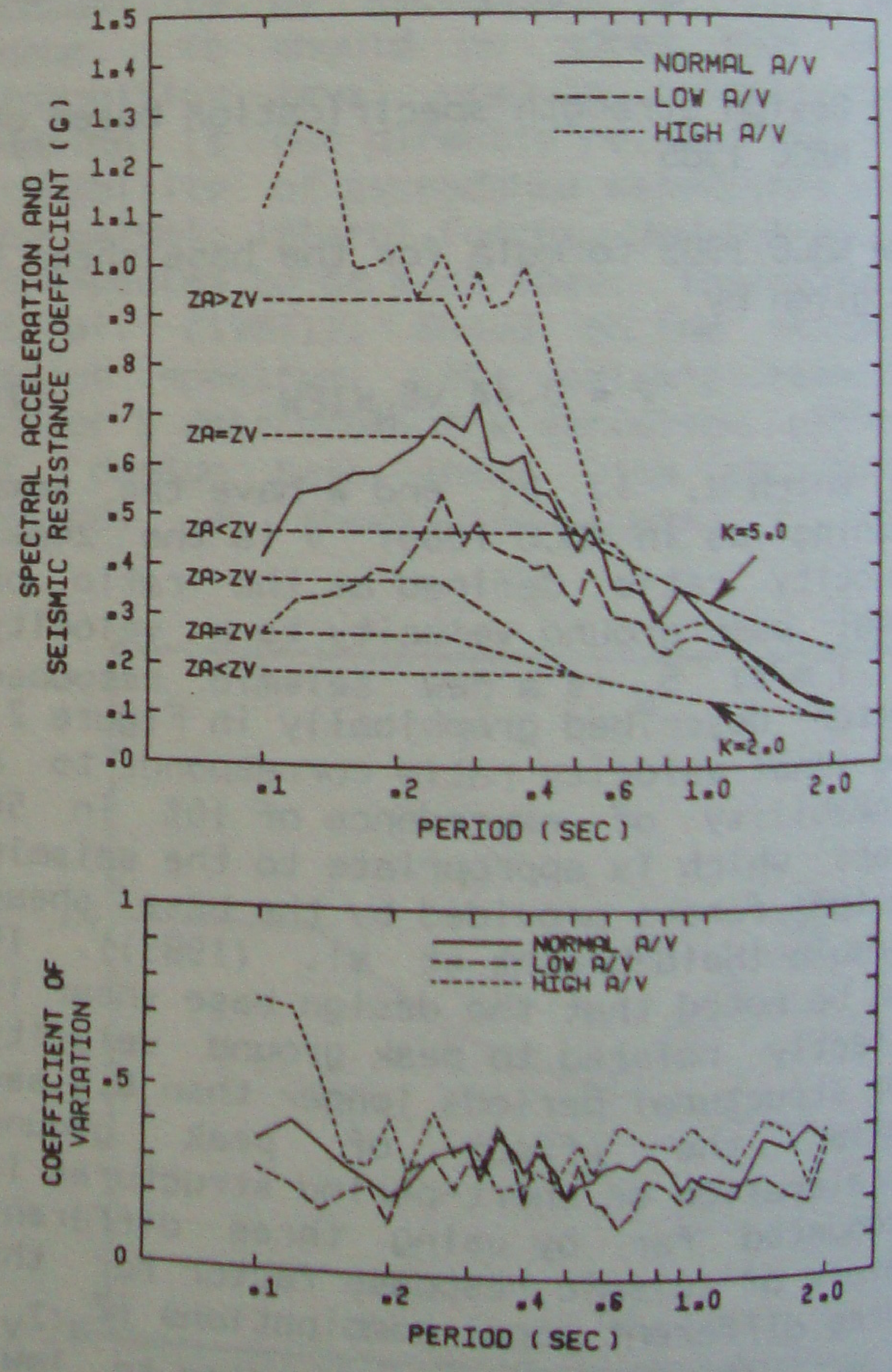

Figure 4. Mean 2% damped elastic acceleration spectra normalized to a peak velocity of 0.2 m/s and seismic resistance coefficients for v=0.2 in NBCC 1985

the seismic resistance coefficient defines the actual yield strength for a corresponding SDOF system. Therefore, the curves of seismic resistance coefficients for different K values can be interpreted as "strength supply" curves for different structural systems. On the other hand, the mean spectral acceleration curves in Figure 3 can be interpreted as the mean "strength demand" curves for structural systems to respond in the elastic range. Once the strength demand exceeds the strength supply, inelastic response can be expected. Shown in Figure 4 are the mean 2% damped elastic acceleration spectra for the three sets of eathquake records normalized to a common peak velocity of 0.2 m/s. Plotted in the same figure are the strength supply curves from equation (6) for K=2.0 and 5.0.

4 SYSTEM RESPONSE STATISTICS

Since the maximum displacement ductility is a traditional parameter characterizing inelastic response in seismic design, it is used as the response index in this study. The mean values of displacement ductility demand are computed for the three sets of earthquake records with different a/v ranges when the yield resistances of the systems are specified from either the base shear formula in NBCC 1980 or that in NBCC 1985. The corresponding coefficients of variation are calculated to illustrate the dispersion characteristics for the computed peak inelastic responses. Since for yield strength specification based on NBCC 1980, all the earthquake accelerograms are normalized to a common peak acceleration and a single seismic response factor is used, the mean values of displacement ductility demand and the corresponding coefficients of variation are also obtained for the whole ensemble of thirty-six earthquake records. Any increase in the coefficient of variation as compared to the analyses based on the three separate sets of records would indicate the significance of a/v ratio as a parameter to reflect the frequency characteristics of earthquake ground motions in a statistical sense.

4.1 Statistical results for NBCC 1980 design

The mean displacement ductility demands are shown in Figure 5 for the three separate sets and the whole ensemble of earthquake records. As can be seen in Figure 5, the mean displacement ductility demands increase with decreasing K value,

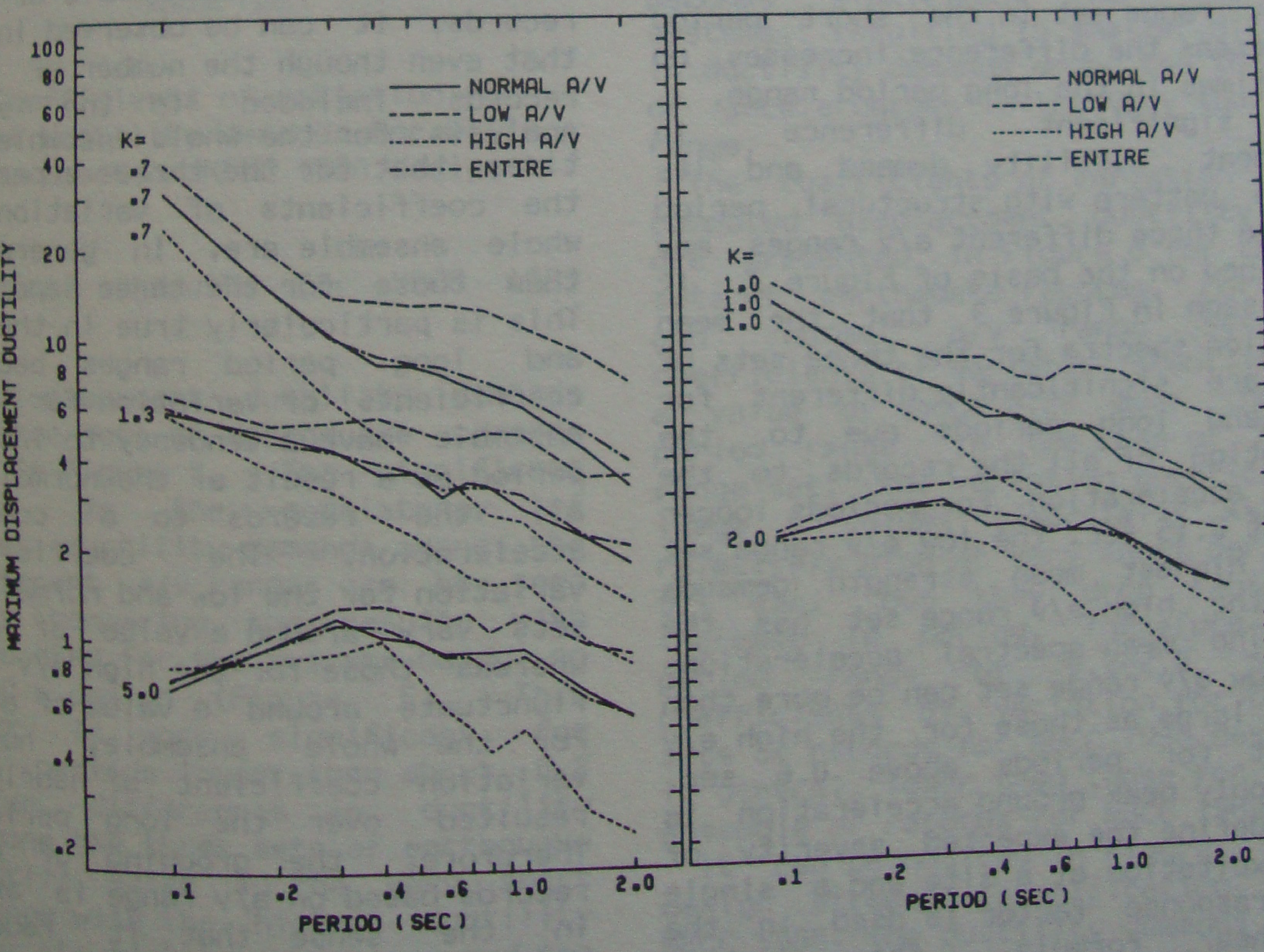

Figure 5. Mean displacement ductility demands for bilinear systems based on NBCC 1980 design

i.e. reducing the design yield strength. However, the variation of ductility demand with structural period is significantly different for the three sets of records. For systems designed with large K values (K=5.0,2.0), the displacement ductility demands for the low a/v range set of records remain essentially constant over the entire period range whereas those for the high a/v range set drop rapidly in the moderate and long period ranges. For systems designed with small K values (K=0.7,1.0,1.3), the ductility demands are generally very high in the short period range and decrease with increase in structural period. However, the decrease is particularly pronounced for the high a/v range set of records in comparison with the other two sets.

It can be observed in Figure 5 that for short-period systems, the ductility demands for large K values do not differ significantly among the three different a/v ranges, but the difference becomes more significant as K value is reduced, i.e. stiff systems are designed with lower yield strength. For long-period systems, there exists significant difference in ductility demand among the three a/v ranges even for large K values, and the difference is particularly pronounced for small K values, i.e. for flexible systems designed with lower yield strength. For example, in the case of K=0.7, the mean ductility demand for the low a/v range set of records is about twice that for the high a/v range set in the short period range whereas the difference increases up to five times in the long period range.

The significant difference in dispalcement ductility demand and its variation pattern with structural period among the three different a/v ranges may be explained on the basis of Figure 3. It can be seen in Figure 3 that the mean acceleration spectra for the three sets of records are significantly different for medium and long periods due to the normalization of all the records to the same peak acceleration. For periods longer than about 0.15 sec, the low a/v range set has the highest mean strength demands whereas the high a/v range set has the lowest. The mean spectral accelerations for the low a/v range set can be more than twice as large as those for the high a/v range set for periods above 0.6 sec. Because only peak ground acceleration is used to define the expected severity of ground excitation at a site and a single seismic response factor is used in the base shear formula, the actual differences in the strength demands for the three sets of accelerograms cannot be considered in the design process. As a result, the use of the same strength supply curve for a specified K value leads to significantly different relationships between strength demands and strength supplies in the moderate and long period ranges for the three sets of ground moitons, resulting in substantially different ductility demands.

The design yield strength corresponding to small K values is sufficiently low that the strength demands for the three sets of earthquake records far exceed the strength supply at short periods. Therefore, the short-period systems are excited into high inelastic response levels, and the reduction of effective stiffness due to yielding becomes very significant. As a result, the effective periods of the systems are elongated (Iwan and Gates (1979)), and the strength demands beyond the initial elastic periods of the systems may reflect the actual excitation intensity associated with the systems. Since the strength demands for the three sets of records are significantly different in the moderate and long period ranges, the differences in ductility demand in the short period range increase as K value is decreased, i.e. design strength is significantly reduced from the strength demand.

Plotted in Figure 6 are the coefficients of variation for the computed displacement ductility demands for the three separate sets and the whole ensemble of earthquake records. It can be observed in Figure 6 that even though the number of earthquake records included in the statisitcal analysis for the whole ensemble is three times that for the three separate sets, the coefficients of variation for the whole ensemble are, in general, higher than those for the three separate sets. This is particularly true in the moderate and long period ranges because the coefficients of variation for the whole ensemble have a tendency to increase with period as a result of the normalization of all the records to a common peak acceleration. The coefficients of variation for the low and normal a/v range sets vary around a value of about 0.3 whereas those for the high a/v range set flunctuate around a value of about 0.4. For the whole ensemble, however, a variation coefficient of nearly 0.7 has resulted over the long period range. Therefore, the grouping of earthquake records based on a/v range is appropriate in the sense that it reduces the dispersion and scatter in the computed peak inelastic responses.

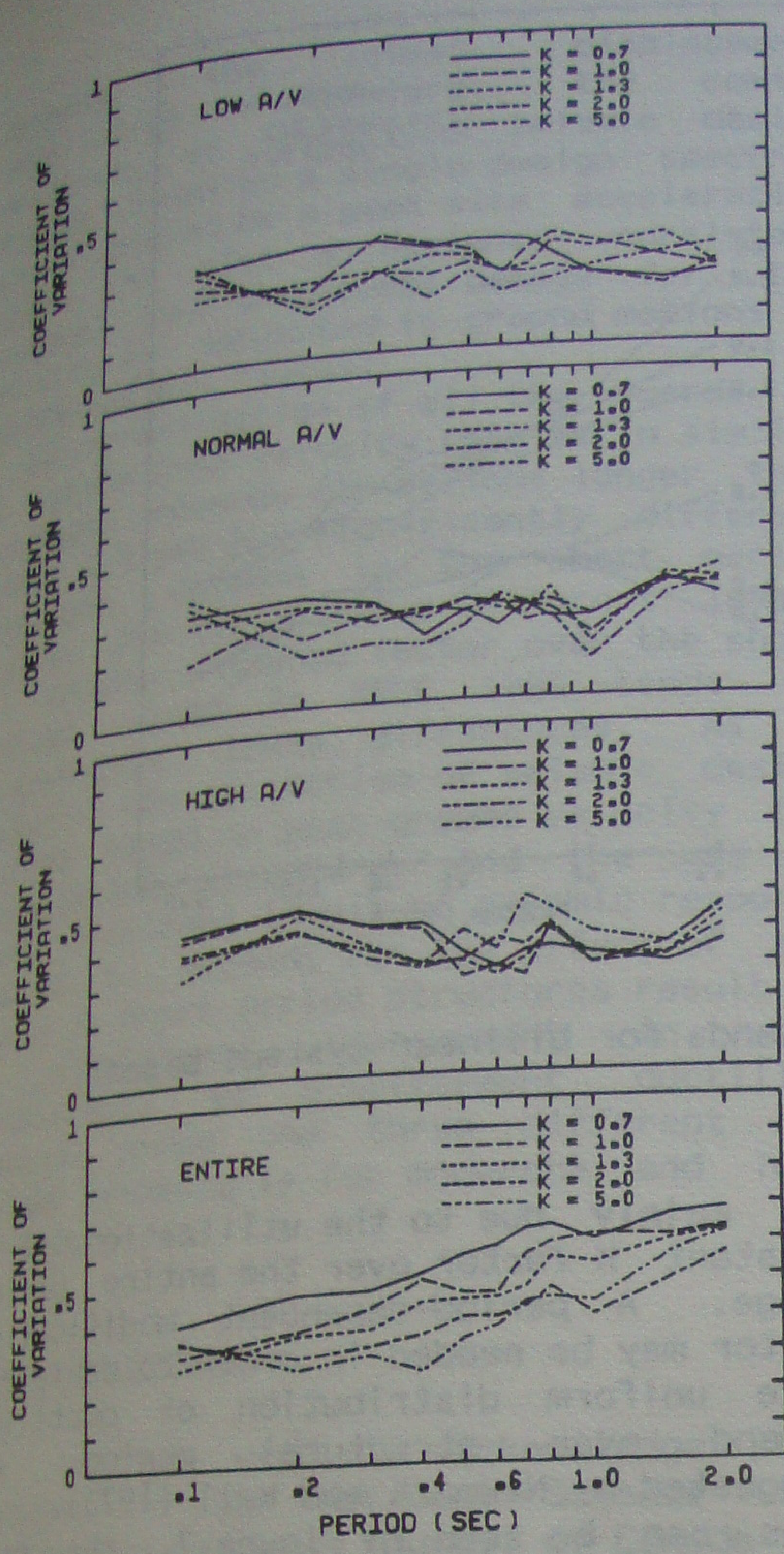

Figure 6. Coefficients of variation for displacement ductility demands for bilinear systems based on NBCC 1980 design

4.2 Statistical results for NBCC 1985 design

The mean displacement ductility demands for the three sets of earthquake records are shown in Figure 7. The significant improvement in the consistency of displacement ductility demands among the three different a/v ranges can be seen clearly by comparing the results with those calculated for the systems based on NBCC 1980 design (Figure 5). This improvement is more significant for structural periods longer than about 0.2 sec. Large differences in ductility demands among the three sets of earthquake records still exist in the very short period range with the highest ductility demands for the high a/v range set and the lowest for the low a/v range set. The differences tend to become smaller for K=0.7, i.e. for short-period systems designed with low yield strength.

The foregoing observations may be explained by referring to Figure 4. Because periods longer than about 0.5 sec fall within the velocity sensitive region, the normalization of all the records to the same peak velocity results in similar strength demands for the three sets of earthquake records for periods longer than 0.5 sec and three plateaus with significantly different strength demands in the short period range. The significant differences in strength demands over the short period range are compensated by using three different strength supply curves for the three sets of accelerograms. As a result, the differences in ductility demands among the three sets of ground moitons are significantly lower than the case in which all the records are normalzed to a common peak acceleration and a single seismic response factor is used in specifying design yield forces. However, even though three different strength supply curves are used in the short period range, the strength demands with respect to the corresponding strength supplies are still the highest for the high a/v range set, as indicated by the relationships between the strength demand curves and the strength supply curves for K=5.0. As a result, the highest displacement ductilities are demanded for the high a/v range set. For K=0.7, the effect of period elongation becomes significant for short-period systems, resulting in smaller differences in ductility demands among the three sets of accelerograms in the very short period range.

The coefficients of variation for the computed displacement ductility demands are presented in Figure 8 for the three sets of earthquake records. For the low and normal a/v range sets, the coefficients of variation stabilize around a value of about 0.25 over the entire period range. In the case of high a/v range set, the variation coefficients for large K values (especially K=2.0) are relatively high at very short periods near 0.1 sec, but they drop rapidly with increase in period. Therefore, in the period range of 0.2-2.0 sec, the coefficients of variation for the three sets of records for NBCC 1985 design are, in general, lower than those for the whole ensemble of records for NBCC 1980 design.

It can be noticed in Figure 7 that for design strength specification based on NBCC 1985, the ductility demands for small K values are still not uniform over the period range considered with very high ductility demands at short periods. This

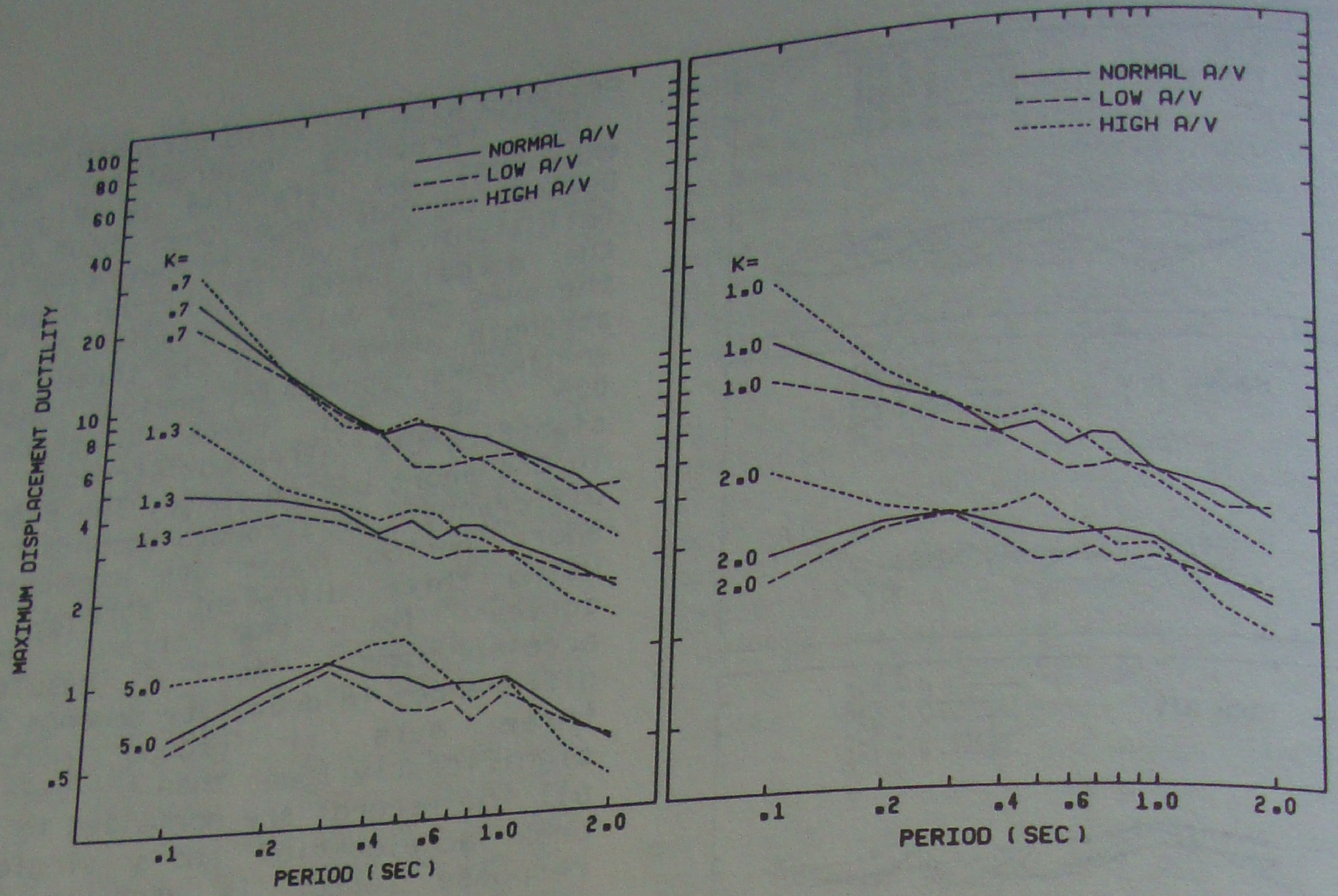

Figure 7. Mean displacement ductility demands for bilinear systems based on NBCC 1985 design

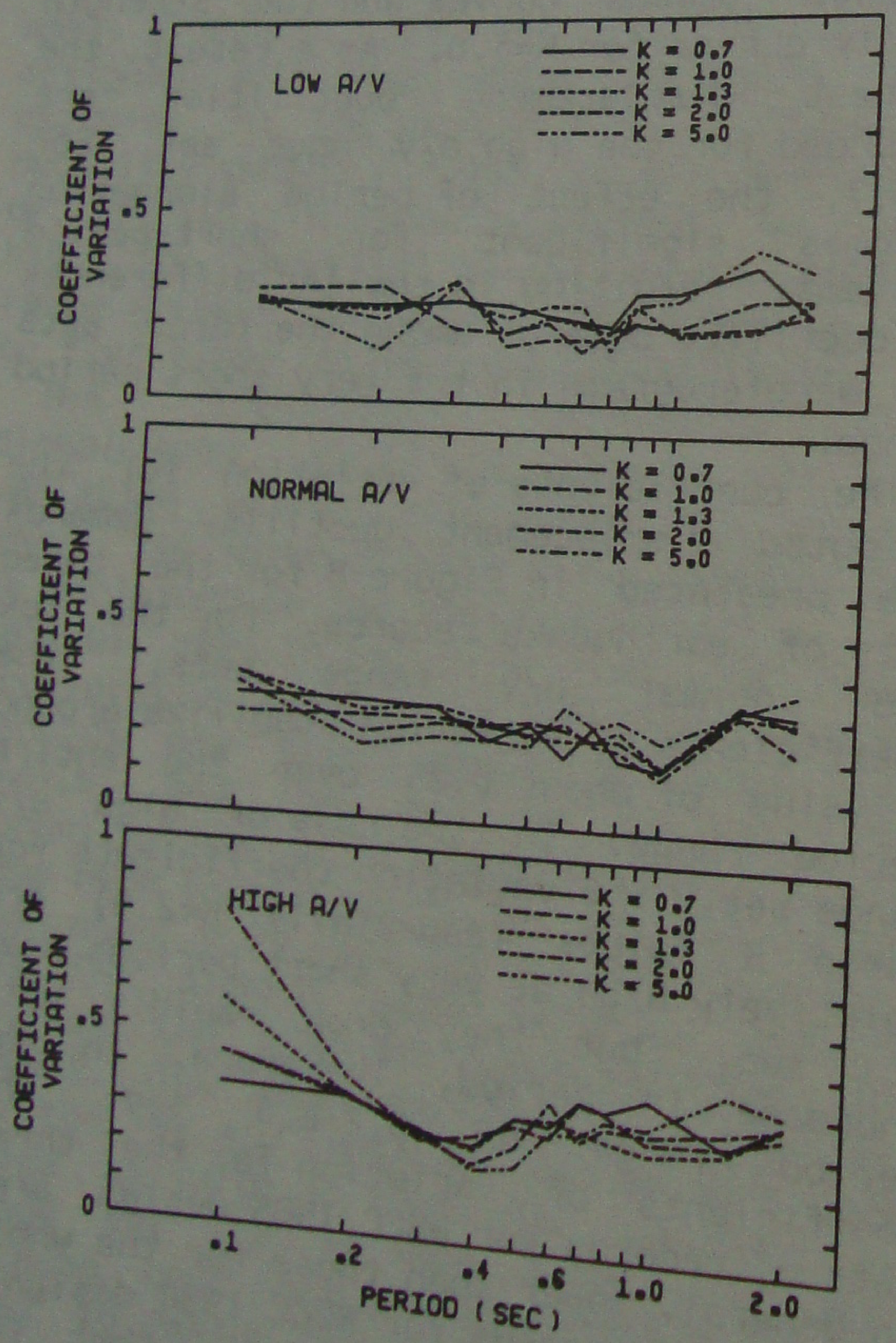

Figure 8. Coefficients of variation for displacement ductility demands for bilinear systems based on NBCC 1985 design

is mainly due to the utilization of a constant K factor over the entire period range. A period-dependent modification factor may be needed in order to achieve a more uniform distribution of ductility demand over structural period, as suggested by Newmark and Hall (1973).

As can be seen in Figure 7, the mean ductility demands for K=5.0 are, in general, slightly less than one for all the three sets of erathquake records. Therefore, structures designed with K=5.0 would generally be excited into the threshold of yielding when subjected to ground motions in all three a/v ranges.

5 CONCLUSIONS

The normalization of all the earthquake records to a common peak acceleration results in significantly different energy contents over the moderate and long period ranges for the three sets of erathquake records with different a/v ranges. As a result, the use of a single design spectrum shape to estimate seismic design forces leads to substantial differences in the displacement ductility demands among the three sets of accelerograms especially for flexible systems designed with low yield strength. The low a/v range set requires the highest displacement ductilities whereas the high a/v range set demands the lowest displacement ductilities. Therefore, the common practice of specifying seismic design forces based on a single design spectrum shape scaled by a peak site acceleration does not give a designer consistent control over structural damage for the structures subjected to ground motions in different a/v ranges.

The normalization of all the records to a common peak velocity results in similar strength demands for periods longer than about 0.5 sec but significantly different strength demands in the short period range. The use of three different levels of seismic response factor over the short period range in NBCC 1985 tends to accommodate these differences. As a result, the estimation of seismic design forces based on peak ground velocity for long-period structures and the use of three different levels of seismic response factor to account for the effect of a/v ratio on short-period structures result in a significant improvement in the consistency of displacement ductility demands among the three different a/v ranges especially for moderate and long periods.

ACKNOWLEDGEMENT

The writers wish to acknowledge the support of the National Science and Engineering Research Council of Canada for the study presented in this paper.

REFERENCES

Associate Committee on the National Building Code. 1980. National Building Code of Canada 1980, NRC No. 17303; Supplement to the National Building Code of Canada 1980, NRC No. 17724. National Research Council of Canada, Ottawa, Ontario.

Associate Committee on the National Building Code. 1985. National Building Code of Canada 1985, NRC No. 23174; Supplement to the National Building Code of Canada 1985, NRC No. 23178. National Research Council of Canada, Ottawa, Ontario.

Bertero, V. V., Herrera, R. A., and Mahin, S. A. 1976. Establishment of design earthquakes - evaluation of present methods. Proceedings of the International Symposium of Earthquake Structural Engineering, Vol. I, St. Louis, Missouri: 551-580.

Bertero, V. V., Mahin, S. A., and Herrera, R. A. 1978. Aseismic design implications of near-fault San Fernando earthquake records. Earthquake Engineering and Structural Dynamics 6: 1304-1313.

Hall, W. J. 1982. Observations on some current issues pertaining to nuclear power plant seismic design. Nuclear Engineering and Design 69: 365-378.

Hall, W. J. and McCabe, S. L. 1986. Observations on spectra and design. Proceedings of the Third U. S. National Conference on Earthquake Engineering, Vol. II, Charleston, South Carolina: 1117-1127.

Heidebrecht, A. C., Basham, P. W., Rainer, J. H., and Berry, M. J. 1983. Engineering applications of new probabilistic seismic ground-motion maps of Canada. Canadian Journal of Civil Engineering 10: 670-680.

Heidebrecht, A. C. and Tso, W. K. 1985. Seismic loading provision changes in National Building Code of Canada 1985. Canadian Journal of Civil Engineering 12: 653-660.

Heidebrecht, A. C., Tso, W. K., and Cherry, S. 1983. Future directions of Canadian seismic code provisions. Annual Conference of Canadian Society of Civil Engineering.

Iwan, W. D. and Gates, N. C. 1979. The effective period and damping of a class of hysteretic structures. Earthquake Engineering and Structural Dynamics 7: 199-211.

Mahin, S. A. and Bertero, V. V. 1981. An evaluation of inelastic seismic design spectra. Journal of the Structural Division, ASCE 107: 1777-1795.

Newmark, N. M. 1975. Seismic design criteria for structures and facilities, Trans-Alaska pipeline systems. Proceedings of the U. S. National Conference on Earthquake Engineering, EERI, Ann Arbor, Michigan: 94-103.

Newmark, N. M. 1976. A rational for development of design spectra for Diablo Canyon reactor facility. Report for the U. S. Nuclear Regulatory Commission. N. M. Newmark Consulting Engineering Services, Urbana, Illinois.

Newmark, N. M. and Hall, W. J. 1973. Procedures and criteria for earthquake resistant design. Building Practices for Disaster Mitigation. Building Science Series No. 46. National Bureau of Standards, Washington, D. C.: 209-236.

Zhu, T. J. 1985. Effect of peak ground acceleration/peak ground velocity ratio on seismic response of simple nonlinear systems. M. Eng. thesis. McMaster University, Hamilton, Ontario.