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Analysis of Strong Motion Records from Uttarkashi Earthquake for Assessment of Code Provisions for Different Seismic Zones

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Strong motion records have been obtained at 13 stations during the Uttarkashi earthquake of October 20, 1991 (magnitude 6.6). A study has been conducted on these time histories to assess the codal provisions in India. Emphasis of the study is on evaluating relative consistency of design provisions for different seismic zones in India. The average response spectra from this earthquake show concentration of significantly more energy in low period range and less energy in high period range. The magnitude of seismic design force for zones I, II, and III is consistent while it is too low for zone IV; no records were obtained in area with shaking intensity corresponding to zone V. It is seen that for buildings in zones I, II, and III, the present design provisions may be lowered either by relaxing the requirement of special ductile detailing, or by reducing the design force. On the other hand, design provisions for zone IV need to be revised upwards.

INTRODUCTION

The Uttarkashi earthquake of October 20, 1991 (magnitude 6.6) in the Garhwal Himalayas in northern India caused strong ground shaking in the districts of Uttarkashi, Tehri, and Chamoli in the state of Uttar Pradesh (Fig. 1). The maximum intensity on Modified Mercalli Intensity (MMI) scale was IX in a region of about 20 sq. km. The area was instrumented with 28 numbers of 3-component strong motion analog accelerographs (SMA-1 of Kinemetrics); of these, 13 accelerographs recorded the event (Chandrasekaran and Das, 1992). Fig. 2 shows the location of these 13 accelerographs as well as the location of epicentre. All the instruments were located in free-field condition (or close to a free-field condition) and the sites could generally be considered as rocky sites. The epicentral distance of these records is in the range of 25 km to 150 km. Table 1 provides the epicentral distance of recording stations, the MMI

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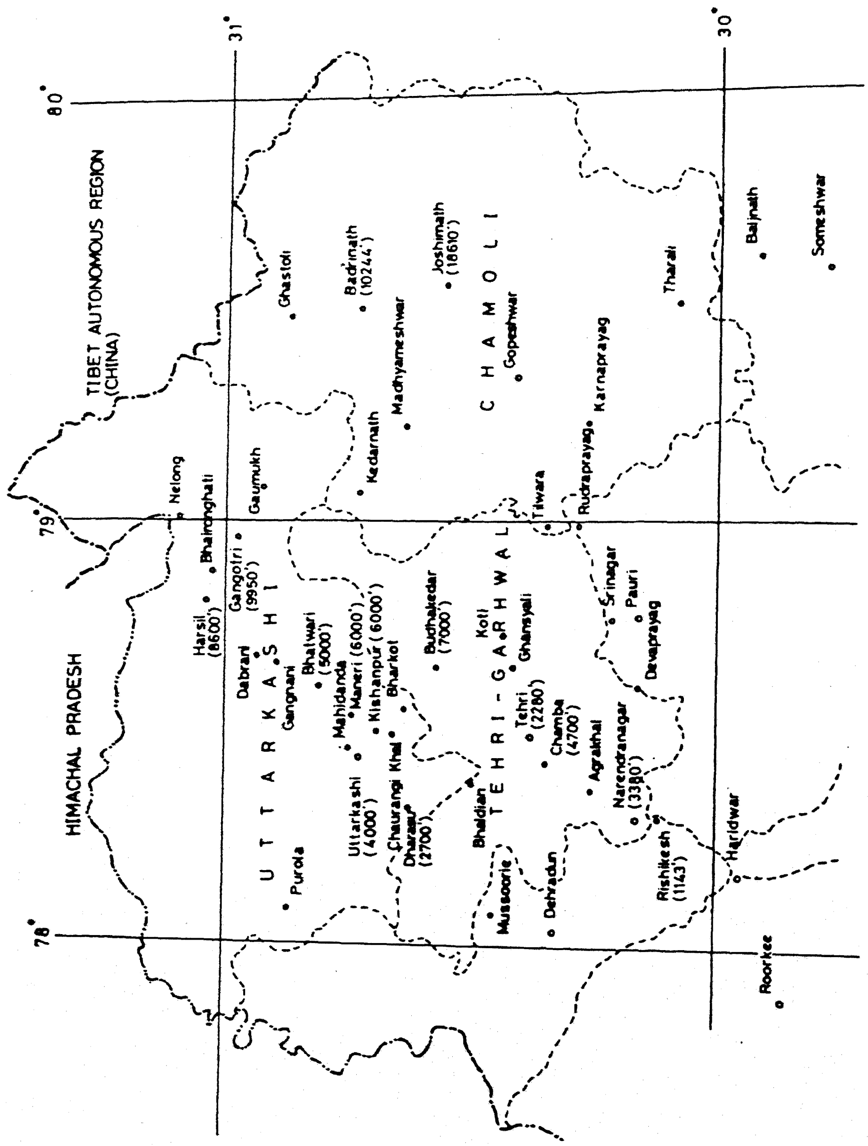

Figure 1 Affected Areas of the Uttarkashi Earthquake

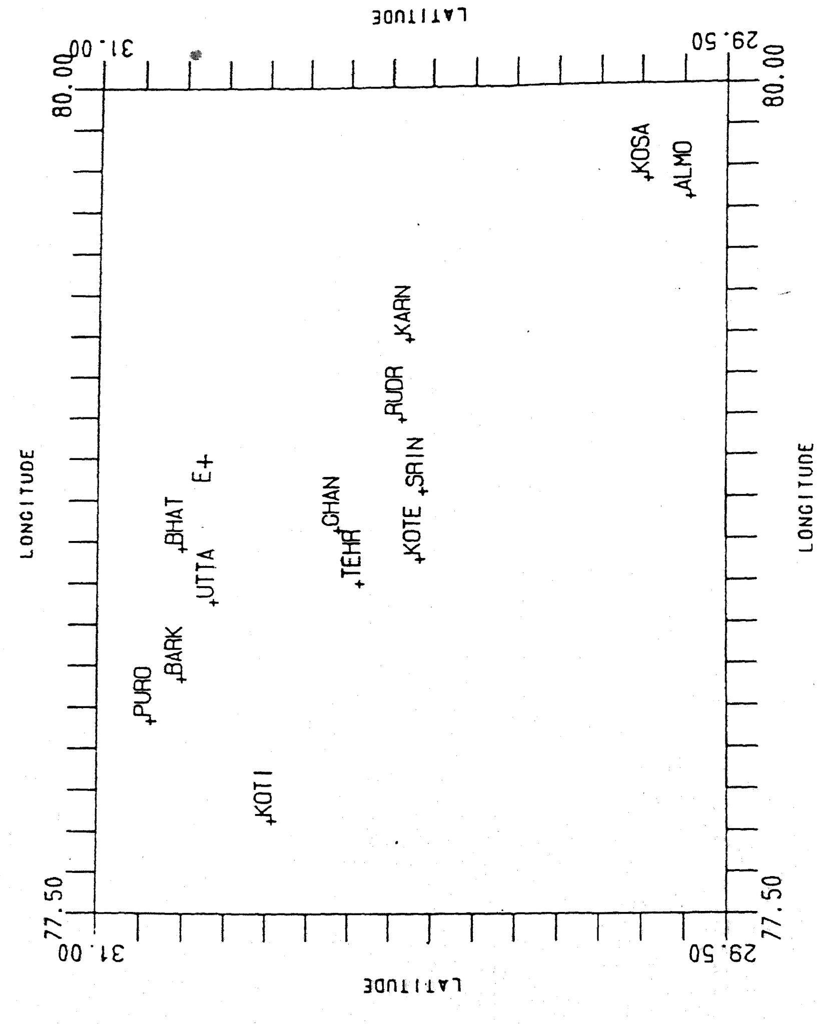

Figure 2 Location of Epicentre and Recording Stations

TABLE 1

Recording Stations and Associated Parameters

Sl. No.	Location	Epi-central Distance (km)	MMI	Dirn.*	Peak Ground Accl. (g)	Peak Ground Vel. (mm/sec)	Peak Ground Displ. (mm)	Spectral Intensity (mm)	A/V Ratio (sec^{-1})
1.	Bhatwari (BHAT)	25	VIII	L	0.253	178.73	37.54	709.73	13.90
				T	0.247	297.78	53.23	1235.36	8.12
				V	0.294	133.65	23.53	500.23	21.61
2.	Uttarkashi (UTTA)	40	VIII$^-$	L	0.242	169.56	21.15	448.86	13.99
				T	0.310	194.68	19.85	579.36	15.61
				V	0.196	141.56	22.98	379.52	13.61
3.	Ghansali (GHAN)	41	VII	L	0.118	80.44	13.57	317.02	14.37
				T	0.117	78.21	13.37	300.50	14.69
				V	0.101	95.94	25.90	353.07	10.34
4.	Rudraprayag (RUDR)	54	VI$^+$	L	0.053	20.70	7.85	77.61	25.26
				T	0.052	27.06	4.01	75.30	18.76
				V	0.045	17.92	3.83	67.08	24.63
5.	Tehri (TEHR)	54	VI	L	0.073	42.15	8.17	184.29	16.94
				T	0.062	92.30	19.84	373.62	6.62
				V	0.059	88.41	23.68	373.71	6.54
6.	Srinagar (SRIN)	59	VI	L	0.067	19.45	5.86	92.77	33.65
				T	0.050	20.20	5.07	93.26	24.48
				V	0.034	35.25	7.62	143.16	9.39
7.	Barkot (BARK)	63	VI$^+$	L	0.095	57.87	10.93	183.37	16.10
				T	0.082	44.84	6.98	148.44	17.95
				V	0.044	27.53	5.62	113.79	15.86
8.	Koteshwar (KOTE)	65	VI	L	0.101	51.55	11.14	194.54	19.18
				T	0.066	39.27	6.78	170.16	16.61
				V	0.076	85.25	20.47	307.53	8.72
9.	Karnaprayag (KARN)	65	VI$^+$	L	0.062	36.90	5.80	103.23	16.53
				T	0.079	37.30	4.02	91.72	20.74
				V	0.026	14.98	2.17	49.81	17.33
10.	Purola (PURO)	76	VI$^+$	L	0.075	48.13	8.44	112.21	15.36
				T	0.093	45.91	9.22	176.59	19.97
				V	0.053	25.57	4.49	77.09	20.23
11.	Koti (KOTI)	105	VI	L	0.021	23.43	4.27	80.44	8.81
				T	0.042	28.60	3.40	91.88	14.32
				V	0.015	17.65	5.05	72.84	8.08
12.	Kosani (KOSA)	144	V$^+$	L	0.029	18.82	3.77	46.16	15.06
				T	0.032	15.55	2.86	45.65	20.26
				V	0.011	9.17	2.41	34.41	12.04
13.	Almora (ALMO)	150	V$^+$	L	0.018	13.32	3.42	45.44	13.07
				T	0.021	12.62	4.50	46.77	16.66
				V	0.019	15.48	3.98	36.61	11.91

* L - Longitudinal, T - Transverse, V - Vertical
** Peak acceleration, velocity, and displacement values are from Ref 2.

applicable to the area around the recording stations, the peak horizontal and vertical parameters (ground acceleration, velocity, and displacement), spectral intensity for 5 % damping (in the period range of 0.1 sec to 2.5 sec), and A/V (peak ground acceleration to peak ground velocity) ratio. The earthquake is characterised by a rather high A/V ratio even at epicentral distance of 150 km. Ground motions with large A/V ratio are known for a rapid decrease in the spectral acceleration with natural period (Tso et al., 1992).

The recorded time histories pertain to the areas which sustained shaking of MMI VIII (two accelerographs), VII (one accelerograph), VI (eight accelerographs), and V (two accelerographs). The seismic zone map for India (IS:1893-1984) divides the country into five seismic zones (I to V) with the associated MMI as V (or less), VI, VII, VIII, and IX (and above), respectively. Thus, the earthquake has provided strong motion records for the design intensity applicable to seismic zones I, II, III, and IV. Objective of this paper is to evaluate, using the available strong motion data, the relative magnitude of design seismic force that is specified by the Indian code for zones I to IV.

The recorded time histories have been assigned to four groups corresponding to seismic zones I, II, III, and IV based on the seismic intensity on MMI scale in the area of the station (Table 2). Thus, Bhatwari and Uttarkashi time histories correspond to seismic zone IV, while those recorded at Ghansali correspond to seismic zone III, etc.

DESIGN CODE PROVISIONS

The code (IS:1893-1984) specifies the design acceleration spectra, $C_s(T,\zeta)$, as

$$C_s(T,\zeta) = K\,\beta\,I\,F_o(S_a/g)\,W \qquad (1)$$

where K is the performance factor which ranges from 1.0 (for structures specially designed for ductility) to 1.6 (for structures not specially designed for ductility); β is soil-foundation factor which ranges from 1.0 (for systems less prone to differential settlement) to 1.5 (for systems highly prone to differential settlement); I is the importance factor which is 1.0 for ordinary structures and 1.5 for important structures; F_o is the seismic zone factor which depends on the seismic zone; and S_a/g is "average acceleration spectrum" shown in Fig. 3. Shape of the spectra in Fig. 3 is the same as the average spectrum curves obtained by Housner using four earthquake time histories recorded in California (e.g., Housner and Jennings, 1982). The code does not specify the value of damping to be used for buildings, however 5% damping is usually adopted. The design spectrum for 5% damping has also been used, with slight modification, in the seismic coefficient method of the code. Therefore, in this paper the code provisions have been evaluated assuming the spectrum for 5% damping as the basis for design.

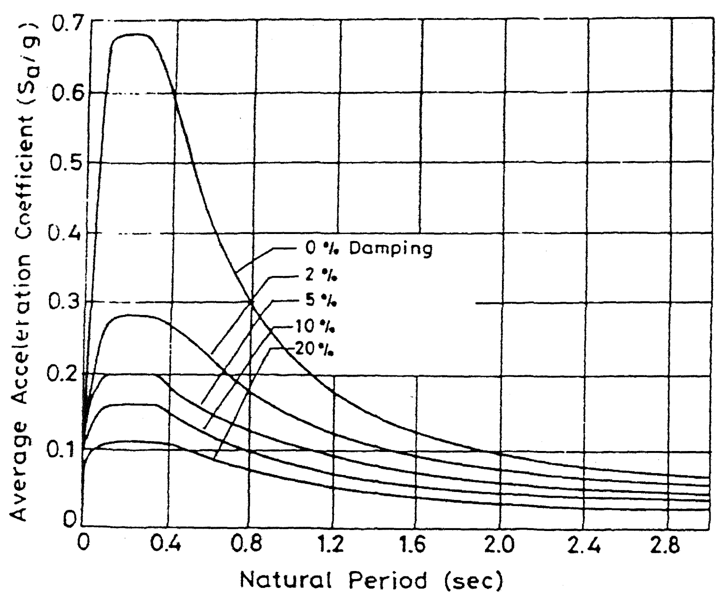

Figure 3 **Average Acceleration Spectra (S_a/g) Specified by IS:1893-1984**

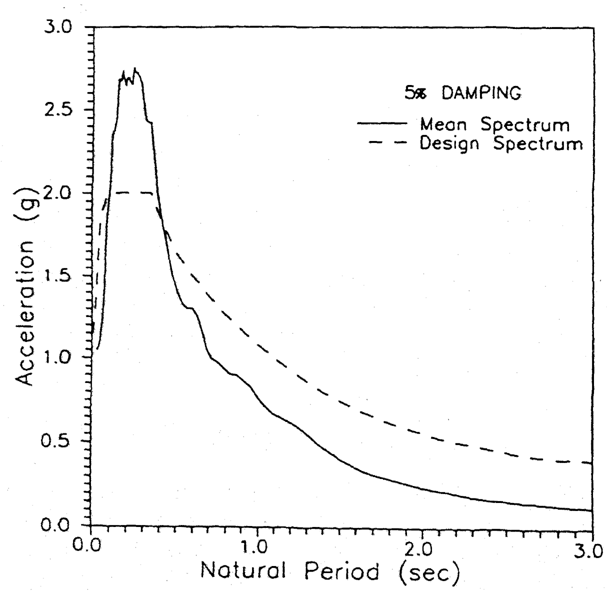

Figure 4 **Comparison of the Mean Response Spectrum With the Design Spectrum (Scaled to Peak Acceleration of 1.0 g)**

TABLE 2

Categorisation of Time Histories for Different Seismic Zones

Sl. No.	Seismic Zone	Associated MMI	No. of Time Histories	Recording Stations
1.	V	IX & above	None	None
2.	IV	VIII	4	1. Bhatwari 2. Uttarkashi
3.	III	VII	2	1. Ghansali
4.	II	VI	16	1. Rudraprayag 2. Tehri 3. Srinagar 4. Barkot 5. Koteshwar 6. Karnaprayag 7. Purola 8. Koti
5.	I	V	4	1. Kosani 2. Almora

The seismic zone factor (F_o) is 0.05, 0.10, 0.20, 0.25, and 0.40, respectively, for zones I to V. While observations on building performance in severe shaking in the past earthquakes seems to have formed the basis of assigning F_o = 0.40 in zone V, the value of F_o for other zones was fixed more or less arbitrarily. While a lot of observational, experimental, and analytical information is available on the required design seismic force for zones of severe shaking in various parts of the world, such data for areas of low or medium shaking is somewhat lacking and this provides motivation for the present study.

RESPONSE SPECTRA

The response spectra obtained for two horizontal components at each of the thirteen stations were scaled for peak ground acceleration of 1.0 g and averaged. Fig. 4 shows the average horizontal spectra (5 % damping); also shown in this figure is the design spectra (5 % damping) specified in the code but scaled to have peak ground acceleration of 1.0 g. Fig. 4 shows that the recorded motion has significantly more energy in

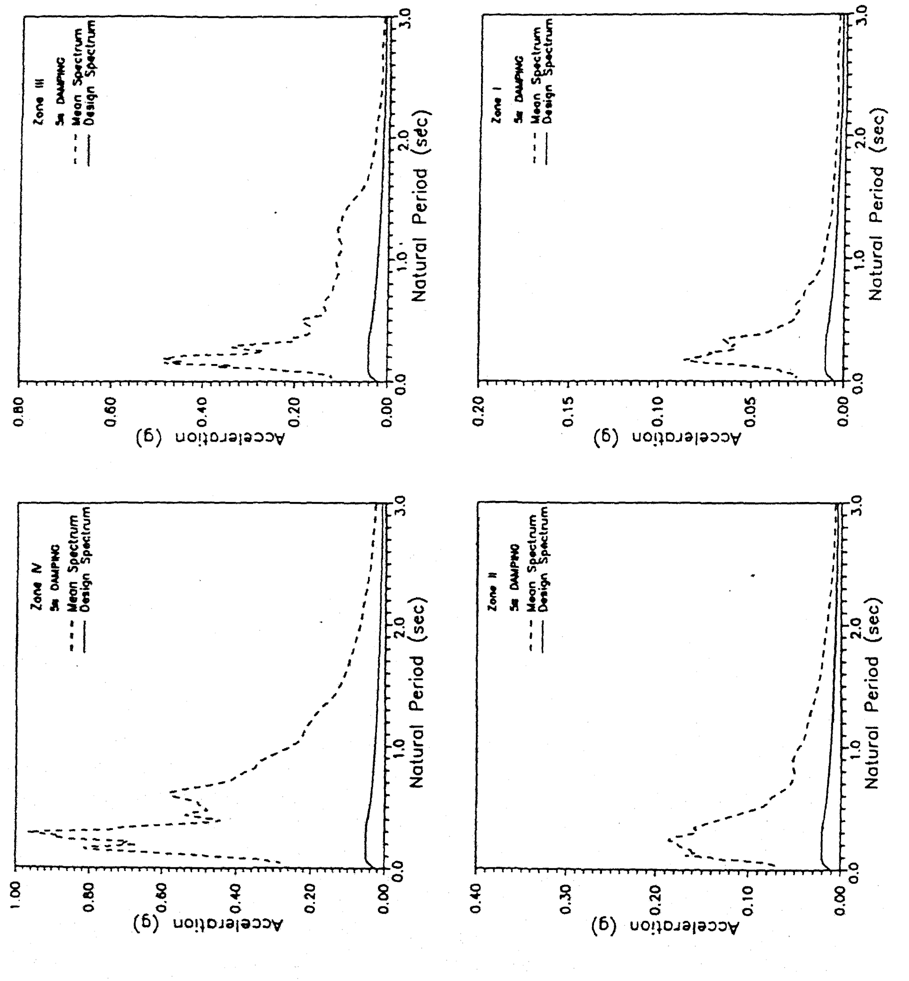

Figure 5 **Comparison of the Mean Response Spectrum and the Design Spectrum for Different Seismic Zones**

the low period range (0 - 0.5 secs) than what is indicated by the code spectra. In the higher period range, the recorded motion has less energy content than that specified by the design spectra. Similar observation has also been made by Chandrasekaran and Das (1990) about the shape of IS code spectra based on a number of earlier recorded motions in the country. Fundamental period of most buildings in the country is less than 0.5 sec, and hence, there is an urgent need to revise shape of the design spectra of the Indian code.

Fig. 5 shows the mean pseudo-acceleration spectra (5 % damping) for horizontal components of the recording stations located in areas of the same MMI. For example, to obtain the curve corresponding to seismic zone IV, the spectra for horizontal components of Bhatwari and Uttarkashi (see Table 2) have been averaged. Also shown in Fig. 5 is the design spectrum for 5% damping as per IS:1893 for the corresponding zone assuming importance factor (I) = 1.0; soil-foundation factor (β) = 1.0; and performance factor (K) = 1.0. Design force lower than the recorded spectra is expected since the code philosophy allows the structure to be damaged in the event of a severe shaking of rare probability, and therefore, the code relies on the overstrength of a structure and on its ductility. However, the ratio of average spectra to the design spectra is rather high in the low frequency range; this is in line with the earlier observation regarding the large energy content in low period range for earthquakes recorded in India. For convenience in comparison, the vertical scale in Fig. 5 has been fixed in proportion to the seismic zone factor for each zone; this makes the design spectra of different zones appear of the same size. Fig. 5 also shows that the ratio of average recorded spectra to the design spectra is much larger in zone IV than it is in the other zones. This issue has been addressed in detail in the subsequent parts of this paper.

OVER STRENGTH AND DUCTILITY

Earthquake design philosophy allows for yielding in case of a strong shaking. The seismic design of ordinary structures takes this fact into account by appropriately reducing, explicitly or implicitly, the design seismic force from what one obtains from an elastic response. The yield load for a structure is significantly higher than the design seismic load. This is because of several factors such as partial safety factors applied to the design load and to the material strength, variation in the strength of material over the specified strength, a higher material strength under cyclic condition over the static condition, strain hardening in steel, redundancy in the structure, additional capacity against gravity loads, contribution of non-structural elements towards lateral strength, etc. (e.g., Uang, 1990). The combined effect of all these factors varies for individual structures and with the design criteria. For a multistorey reinforced concrete frame building, the overstrength may range from 2.0 to 3.0, or even more. The subsequent analysis assumes an overstrength factor of 2.25, i.e., the yield seismic load for the structure is about 2.25 times the code specified design seismic load.

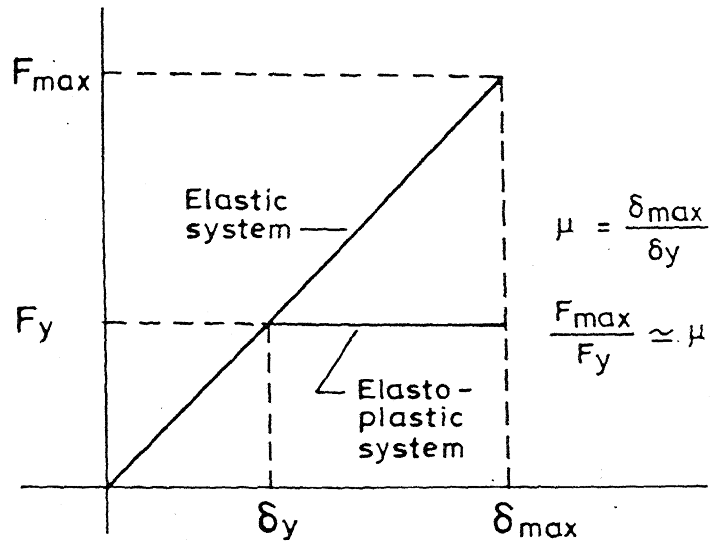

Figure 6 Elasto-Plastic System.

The post-yield deformation makes the structure absorb a higher amount of energy through hysteresis and this reduces the response (seismic force) of the structure. For instance, for large period structures (with natural period more than 0.5 secs), a ductility factor of μ (ratio of ultimate deformation to the yield deformation) causes the response of an elasto-plastic structure to reduce approximately by a factor of μ over the elastic response (Fig. 6). In the lower period range, ductility is somewhat less effective in reducing the response, and in case of a rigid structure the ductility does not reduce the response (Riddell et al., 1989). Seismic codes also rely on the ductility of a structure to reduce the design force and therefore specify a somewhat larger design force for a less ductile structure.

Prior to the 1984 edition of IS:1893, the code requirement was that a structure be detailed for ductility as per IS:4326 if the product $\beta I F_o$ equals or exceeds 0.25; this always happened in seismic zones IV and V, and sometimes in lower zones for β and / or I greater than 1.0. Thus, the design seismic force was not an explicit function of the ductility, but it was expected that structures in zones IV and V, as well as important structures (and those with high susceptibility to differential settlement) in lower seismic zones, will be designed to have higher ductility. The 1984 edition of the code has introduced the term performance factor (K) for calculation of design seismic force. The code now requires that, irrespective of the seismic zone, whenever the structure is detailed for ductility as per IS:4326, K will be taken as 1.0, and it is 1.6 otherwise (with a value of 1.3 for somewhat intermediate situations). In other words, if special ductile detailing is

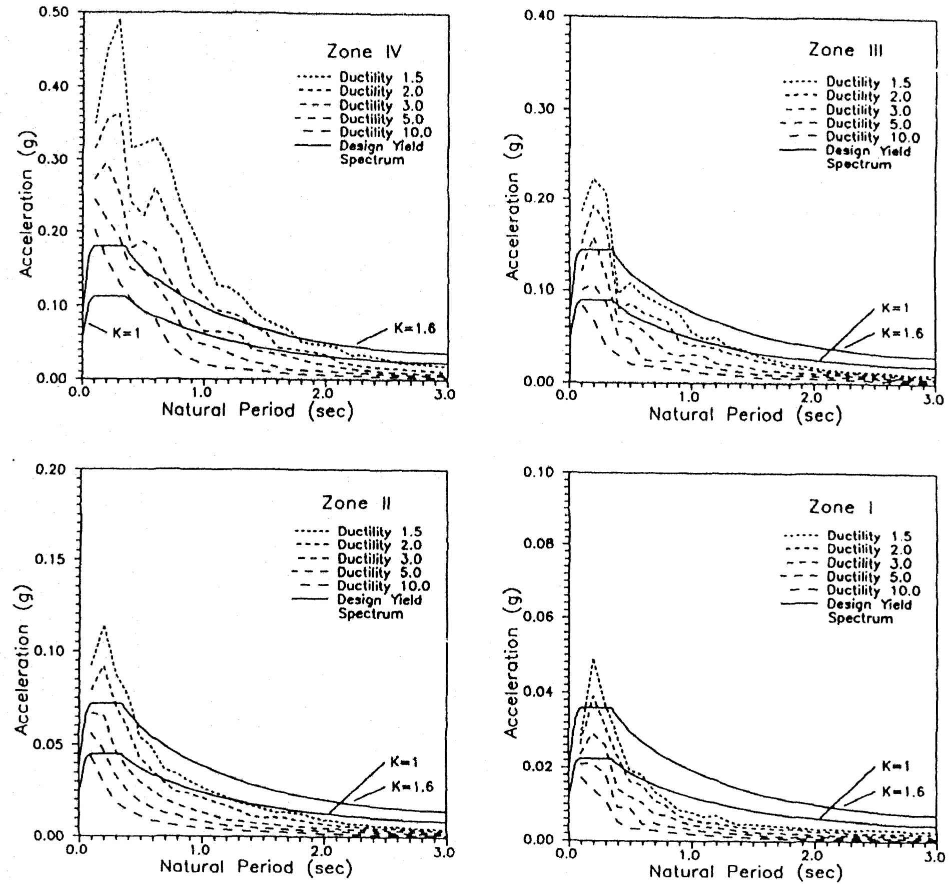

Figure 7 **Comparison of the Design Yield Spectrum with the Mean Non-Linear Response Spectrum for Different Seismic Zones (5% damping)**

not followed even in zones I, II, and III, the code now provides for design seismic force which is 1.6 times what it was prior to the 1984 edition. The issue of ductility in different zones and the level of design seismic force has been examined in light of the strong motion data in the next section .

NON-LINEAR SPECTRA AND DUCTILITY DEMAND

Non-linear response spectra were obtained for elasto-plastic systems for horizontal components of the accelerograms. Fig. 7 shows the pseudo-acceleration ($\omega^2 u_y$) spectra for an elasto-plastic system averaged for records obtained in areas of different MMI. Also, plotted in Fig. 7 is the "design yield spectrum" for the corresponding seismic zones both for K = 1.0 and K = 1.6. The design yield force has been obtained by assuming importance factor (I) = 1.0; soil-foundation factor (β) = 1.0; and an overstrength factor = 2.25. This gives the design yield force for a single degree of freedom structure as $F_{yield} = 2.25\ K\ F_o(S_a/g)W$, and therefore, design yield spectrum, C_y, as

$$C_y = F_{yield}/\ W = 2.25\ K\ F_o\ (S_a/g) \qquad (2)$$

Fig. 7 reveals that in seismic zones I, II, and III, structures with K = 1.0 require a ductility of about 5 in the period range 0.1 sec to 0.3 sec; beyond 0.3 sec a ductility of 3.0 is usually adequate, and for natural period higher than 1.5 sec (0.7 sec for zone I), a ductility of 1.5 is also adequate. Thus, the relative magnitude of design force for the three zones are consistent with the intensity of shaking expected. If the performance factor (K) equal to 1.6 is applied in these zones, as is now required by the code if ductile detailing is not followed, then the ductility demand in low period range is further reduced to about 2.0. On the other hand, the inelastic response spectra in zone IV are much higher than the design yield level when compared to that for the lower zones. It is clear that the relative magnitude of design force for zone IV is inconsistent with that for the lower zones; that is, either the design provision for zone IV is unconservative or that for zones I to III is too conservative.

To evaluate the amount of ductility structures designed for different seismic zones must possess to withstand the ground shaking, ductility demand curves have been obtained for different seismic zones. The design yield force to arrive at the ductility demand has been obtained as discussed earlier and shown in Fig. 7 with solid line (for K = 1.0). The ductility demand curves obtained for different time histories were averaged zone wise and are plotted in Fig. 8. The very high ductility demand at low periods is obviously due to the fact that at low periods, ductility is not very effective in reducing the response. A multistorey building, if designed, detailed, and constructed appropriately, can be expected to have an overall structural ductility of about 3 to 5. Results of zones I, II, and III show that the maximum ductility required is about 5, 10, and 8, respectively, in case of structures with low natural periods and with K = 1.0. Even though such

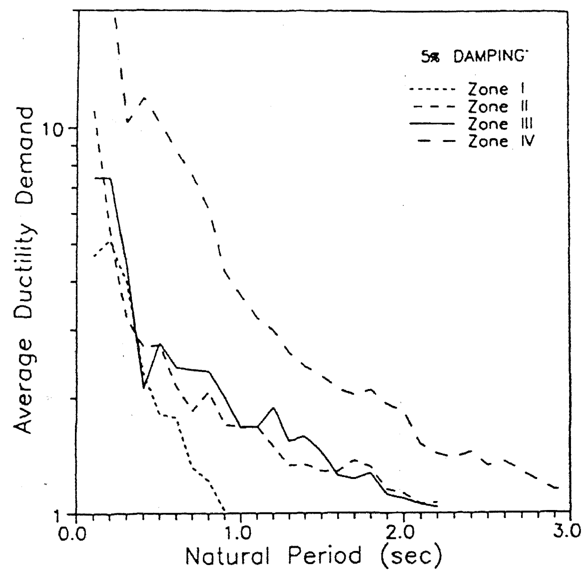

Figure 8 **Comparison of Average Ductility Demand for Different Zones (with K = 1.0)**

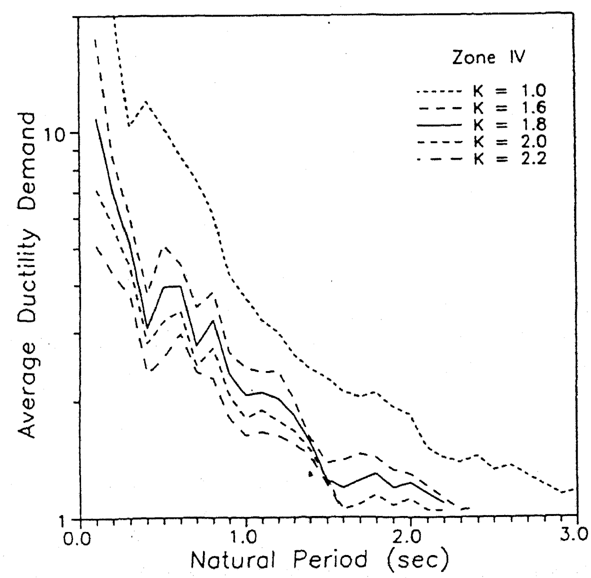

Figure 9 **Comparison of Ductility Demand for Zone IV with Different Values of K**

values of ductility cannot be achieved without special ductile detailing, this appears acceptable for low-rise R.C. frame buildings with brick masonry infills; the common mode of construction in India. Masonry infill walls in such structures contribute significant strength and energy dissipation which are difficult to quantify and hence are neglected in design; such walls are ususally treated as non-structural. Therefore, provisions regarding the performance factor (K) equal to 1.6 for these zones or special ductile detailing required by the 1984 edition of the code seem to be somewhat too conservative. Buildings in such zones can be expected to perform satisfactorily if designed as per ordinary detailing procedures and with K = 1.0. However, many other structures, such as bridges, do not have non-structural elements to assist in withstanding the seismic load and cannot exhibit much ductility; the design provisions for such structures need to be increased in these zones. This can be done by incorporating a suitable value of performance factor (K) for such structures in the design code; the present codal provisions do not specify K for these structures and hence such structures are at present designed for about the same base shear coefficient as a specially detailed ductile building. The ductility demand curves show that in high period range the code specifications are quite conservative and these can possibly be reduced by lowering the design spectrum in the high period range.

Ductility demand curves for zone IV, when compared with those for the other zones (Fig. 8) show that the design provisions for zone IV need to be upgraded, particularly for low natural period range. Fig. 9 shows the ductility demand curves for zone IV assuming K = 1.0, 1.6, 1.8, 2.0, and 2.2. Ductility demand for structures of period 0.1 sec is around 60 with K = 1.0, 18 with K = 1.6, 10 with K = 1.8, and 7 with K = 2.0. The ductility demand curve in this zone with K = 2.0 (Fig. 9) is comparable to that for zones II and III with K = 1.0 (Fig. 8). Thus, the design force for this zone should be about 2.5 times (as against the present 1.25 times) that for zone III if comparable ductility is provided in all the zones. Since we have observed earlier that introduction of K = 1.6 in lower zones is unnecessary and could be removed even with ordinary detailing, the design provisions for zone IV could be made consistent with those for the lower seismic zones without having to increase the design force by a factor of 2.0. For instance, the zone factor (F_o) for zone IV may be increased from the present 0.25 to 0.30 (or even 0.35), and the ductile detailing should be insisted upon in this zone if K = 1.0 is used. In case of ordinary detailing, K = 1.6 with the suggested increase in F_o will make the design force for this zone about 2.5 times that for zone III.

RECOMMENDATIONS

Based on the limited strong motion data which formed the basis of this analysis, the following recommendations are made. These need to be substantiated by conducting similar studies on data from other Indian earthquakes.

a) The shape of design spectra in the code is somewhat unconservative in low period range and conservative in high period range. There is an urgent need to review and possibly revise the code specified spectra. This should be done considering the ground motion characteristics in India for earthquakes of different magnitude and at different epicentral distances, non-linear response, ductility and its effectiveness in reducing the response particularly in the low period range.

b) The present design seismic force for buildings in zones I, II, and III is adequate even in the low period range with K = 1.0 and with ordinary detailing. In other words, provisions introduced in the 1984 edition of the code requiring the buildings to be designed for K = 1.6 with ordinary detailing and with K = 1.0 with special ductile detailing even for low seismic zones are too conservative and should be removed.

c) The code provisions for zone IV are unconservative and need to be upgraded. With special ductile detailing, the design force for buildings in low period range need to be increased by at least 20% - 30% of what is now provided by the code. For buildings not specially designed and detailed for ductility, the value of K = 1.6, over and above the proposed increase of 20% - 30%, is adequate.

d) Structures other than buildings which do not have significant non-structural elements and redundancy, and therefore cannot provide the ductility and energy absorption comparable to that for buildings, need to be designed for significantly higher base shear coefficient than the buildings; codes in many other countries already do so. The Indian code needs to be revised in this regard.

CONCLUSION

The average response spectra from this earthquake show concentration of significantly more energy in low period range and less energy in high period range. This has also been observed for several other Indian earthquakes and therefore there is an urgent need to review the shape of design spectrum in the code.

The relative magnitude of design seismic force for zones I, II, and III is consistent but too low for zone IV. Buildings in zones I, II, and III are expected to perform adequately with the present design force but with K = 1.0 and ordinary detailing. Thus, the design provisions for these buildings could be reduced and brought back to the pre-1984 levels. The design seismic force for zone IV need to be increased by about 20% - 30% from the present level (i.e., post 1984 level).

The design seismic force for structures other than buildings, which cannot provide comparable ductility and energy dissipation, need to be increased significantly. This observation is consistent with the current trend in many other countries.

Similar studies need to be conducted using strong motion data obtained from many other earthquakes in India. Moreover, the present set did not provide any data corresponding to seismic zone V. We have not yet obtained a strong motion record in the country from area that sustained shaking of MMI IX or above, the intensity applicable for seismic zone V.

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