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Seismic Zonation of India

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SYNOPSIS : The Himalayan belt, Indo-Gangetic Plains and Peninsular shield divide India in three major regions with decreasing seismic potential. The Indian Standard Criteria for Earthquake Resistant Design of Structures (IS : 1893-1984) incorporate a seismic zoning map (SZM) demarcating five seismic zones, which show zones with many islands, and prescribed design parameters for the delineated zones do not show consistent exceedance probability. A probabilistic analysis has been carried out and seismic design ground motion parameters have been estimated for 100 years service life, which do not support delineation of five zones with uniform ratio of seismic hazard among various zones. Four seismic zones have been delineated expressing gross areal hazard and weighted average of design response acceleration have been evaluated for firm ground conditions in each zone. Guidelines to take into consideration effects on design ground motion parameters due to rock and soil cover overlying underground structures, and excitation of hill ranges bordering deep valleys in mountainous terrains have been indicated.

INTRODUCTION

Provision of adequate earthquake resistance in buildings, life-line structures and other civil works is the principal method of mitigation of earthquake hazards. A quantitative assessment of the earthquake hazard is therefore needed to examine the vulnerability of existing structures and design of new structures. Bureau of Indian Standards (formerly known as Indian Standards Institution) brought out the first Indian Standard Rcommendations for Earthquake Resistant Design of Structures (IS: 1893-1962) which incorporated a SZM to indicate broadly the parameters to be adopted for earthquake resistant design in different parts of the country. Srivastava (1969, 1974) has described the basis and procedure adopted in the prepration of 1962 SZM (Fig. 1) and its subsequent revisions in 1966 and 1970. 1970 SZM (Fig. 2) demarcate regions with modified Mercalli (MM) intensity " V and less ", VI, VII, VIII and " IX and above " as seismic zones I, II, III, IV and V respectively. Five generalised tectonics units (Fig. 3) with decreasing magnitude and frequency of earthquake occurence (Krishnaswamy 1969 in Srivastava, 1969) were considered in evaluating the intensity of earthquake by deterministic approach. Though a reasonable estimate of the likely maximum magnitude in each of the demarcated seismic zone could be obtained, little information was available on depth of focii of such events, and establish known tectonic features in various tectonic units as seismic source zones. Thus estimated maximum intensities around tectonic features to work out design value are tentative till it is confirmed from strong ground motion records in future. The 1970 SZM which is now under revision, show zones with many islands, and prescribed design parameters for the delineated zones donot show consistant exceedance probability for a specified exposure period or service life of structures.

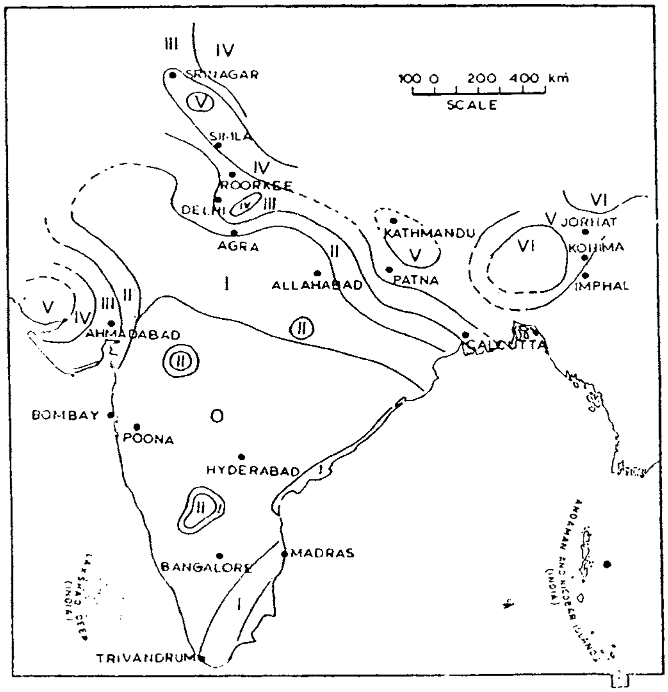

Figure 1. 1962 Seismic Zoning Map of India (IS: 1893-1962).

The primary objective in the preparation of SZM is to prescribe design force to ensure the desired safety of the structures during their life time on exposure to the maximum credible earthquake, commensurate with cost - benifit ratio limited by economic and social considerations and to prevent disaster. A rational basis is therefore required in prediction of design seismic force due to the probable intensity of ground motion resulting from earthquake occurrence in future in different parts of the country and demarcate the seismic zones accordingly. As data on earthquake occurrence is not deterministic, it is appropriate to evaluate the ground motion parameters from probabilistic approach combining statistical and seismotectonic approaches.

EARTHQUAKE OCCURRENCE

Data on earthquake occurrence in the past indicates that possibilities of occurrence of an earthquake in future can not be ruled out for any part of India. Correlating the geology and tectonics with known epicentres of earthquakes (Fig. 4), a definite pattern of earthquake activity is observed, which indicate that all these earthquakes are of tectonic origin. In northern Himalayan belt abuting Indo-Gangetic plains (Fig. 3), earthquake are considered to be associated with ruptures along under thrusting plane of Indian plate and faults transverse to Himalayan belt following Peninsuler-Shield lineaments in this region of youthfull mountains. North - East India in this Himalayan belt shows highest seismic activity as the region forms a complex interplate terrain along continent - continent (Indian and Tibetan plates) convergence in its north - western parts, over thrusting Burmese plate along its eastern margins and over thrusting Mishmi block in its north-estern area (Fig. 5). In alluvial tracts bordering Himalayan belt, earthquakes are considered to be related to fractures along major faults and rifts in the basement underlying the sedimentary cover, and in the Indian Peninsular Shield with various faults and rifts. Some of the faults and thrusts considered to be associated with earthquake occurrence have been well demarcated, while the likely presence of others is indicated by indirect inference based on geophysical information and data on earthquake occurrence. The causative forces which produce ruptures releasing seismic energy are not fully known and various views have been expressed regarding them. Based on theories of plate tectonics and ocean floor spreading the Himalayan belt is considered to form an interplate zone and continued convergence appears to be the main cause for earthquakes with magnitude 6.5 or more which occur frequently.

Indian Peninsular shield, whose extensions form the surrounding basement of the sedimentary and alluvial basins form an intraplate zone. The western parts and coastal terrain show relatively higher seismic activity in relation to other parts of the Peninsular shield. Cymatogenic warping of the crust due to subcrustal currents coupled with isostatic readjustment appears to be possible mechanism for earthquake occurrence. Although small earthquake tremors are felt in various parts of

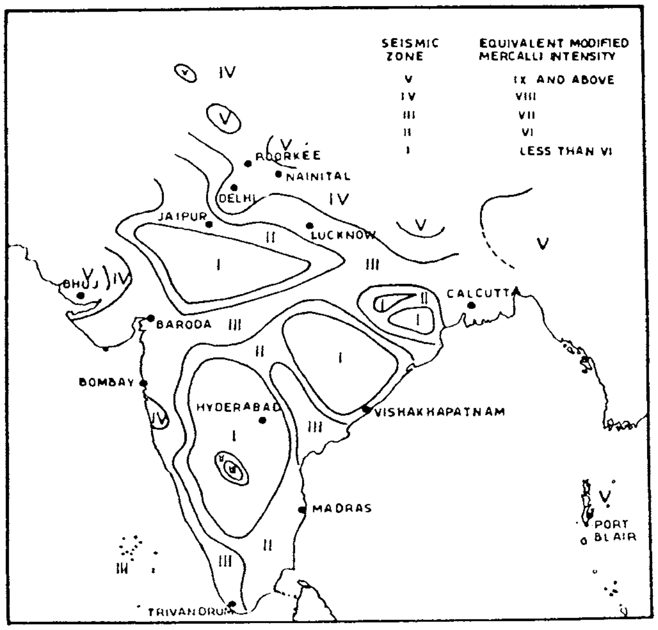

Figure 2. 1970 Seismic Zoning Map of India (IS: 1893-1984).

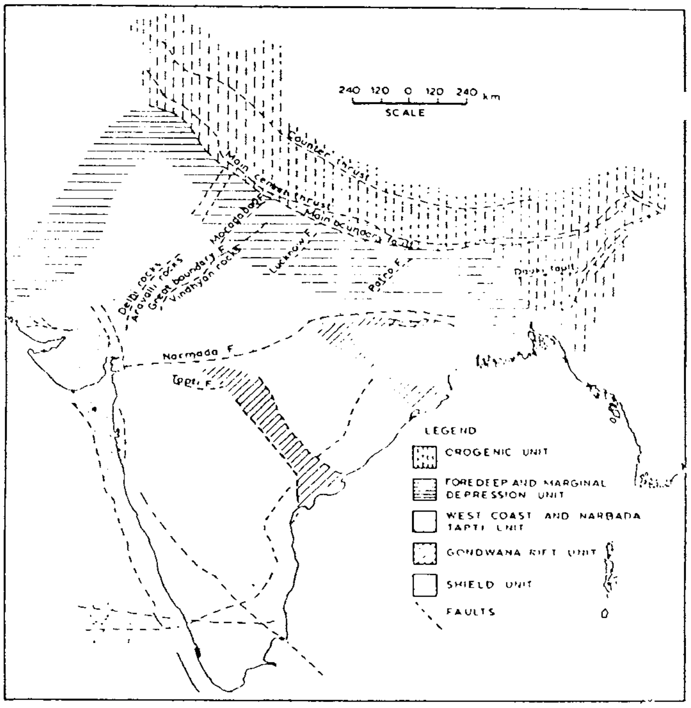

Figure 3. Map Showing Generalised Tectonic Unit of Indian Shield and Himalayan belt (Srivastava, 1974).

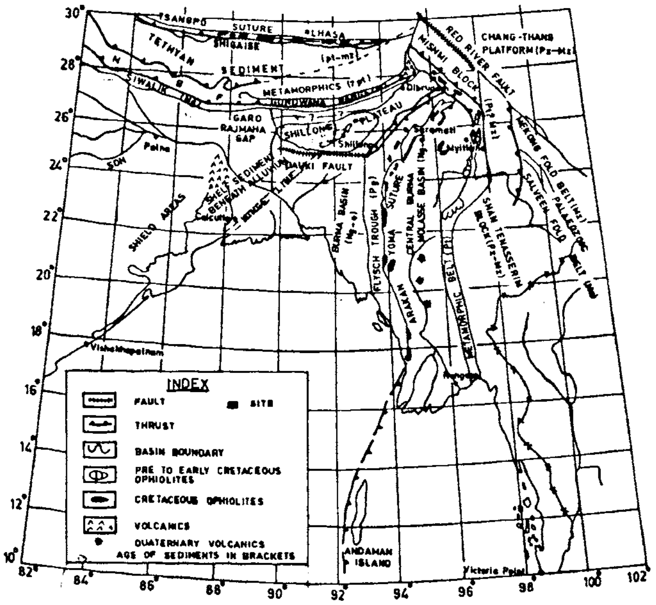

Figure 4. Generalised Tectonic Map of North East India and Adjoining areas (After Nandy, 1982).

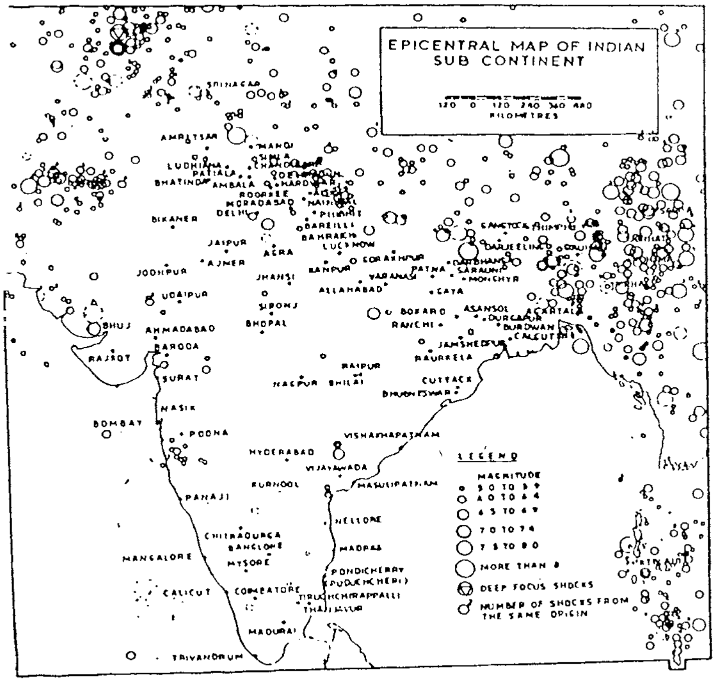

Figure 5. Epicentral Map of Indian Subcontinent.

Indian Peninsular Shield and its surrounding basins, data on earthquake occurrence indicates that there were comparatively large periods of quiteness with shorter period of activity as compared to the very frequent earthquake occurrence in northern Himalayan belt.

PROBABILISTIC APPROACH

Basu and Srivastava (1981) estimated 100 years effective peak ground acceleration (EPGA) with 0.5 exceedance probability in Indian subcontinent (Fig. 6). The analysis considered the region to be non-homogeneous in seismotectonic features. The Himalayan belt was subdivided into three macro seismic provinces postulated by Srivastava et. al. (1974) and Peninsular Shield with its surrounding sedimentary basins as one broad seismotectonic province. Seismically active structures (major faults, rift etc., whose extensions could be related to known epicentres) were taken as area source within these broad seismotectonic provinces. Following on similar lines 100 year peak ground acceleration (PGA) with 0.5 exceedance probability were estimated at grid points using data of earthquakes occurrence from 1917 onwards as epicentral locations of earlier events are not known with desired accuracy. In the adopted model a volume source of 150 km radius arround grid points at the surface of the earth and focal depth of 150 km is considered for floating earthquakes as volume source, and faults lying within this volume are considered as planer sources. It is assumed that spacial distribution of occurrence of earthquake are equally likely in Longitude and Latitude. Focal depth H of earthquakes is considered to follow truncated mixed log-normal distribution

$$f_H(h)=\sum_{i=1}^{2} p_i \exp[-(\ln h-\nu)^2/(2v_i)]/\{\sqrt{2\pi v_i}\,\Phi[(\ln H_o-\nu)/\sqrt{v_i}]\}$$

where $0 < p_1 < 1$; $p_2 = 1-p_1$; $v_1 > v_2 > 0$;
$h \in [0, H_o = 150 \text{ km}]$ (1)

and $\Phi(.)$ probability distribution function $N(0,1)$. The estimation of parameters (p_1, ν, v_1, v_2) were formulated as minimum chi-square problem.

The magnitude M was assumed to be independent of earthquake occurrence. The magnitude distribution were estimated from two distribution depending on availability of data (at least twenty events) as
(i) Biomodal (mixed truncated exponential)

$$f_M(m)=K_1\beta \exp[(m_o-m)\beta+(m_1-m)\lambda\, U(m-m_1)] \quad ; \quad m \in [m_o, m_2]$$

$$\text{where } 1/K_1=[\lambda+\beta-\lambda \exp\{(m_o-m_1)\beta\}-\beta \exp\{(m_o-m_2)\beta+(m_1+m_2)\lambda\}]/(\lambda+\beta) \qquad (2)$$

$U(.)$ is a Unit step function and $m_o = 5 < m_1 < m_2$. The estimation (λ, β, m_1) are formulated as minimum chi-square problem.

(ii) truncated exponential

$$f_M(m)=K_2\beta \exp[(m_o-m)\beta] \quad ; \quad m \quad [m_o, m_2]$$

$$\text{where } 1/K_2=1-\exp[(m_o-m_2)\beta] \qquad (3)$$

m_2 are assumed from historical data and was estimated. The attenuation is taken as a random law with

$$Y=5600\ \exp[0.8M-2\ \ln(R+40)+\epsilon] \tag{4}$$

where Y is the PGA in gal, M is the magnitude and R is focal distance. ϵ is a normal random variable having mean 0.04 and variance 0.4096 as reported by Esteva and Villaverde (1974).

The occurrence of an earthquake in each source was assumed to be Poisson with intensity μ_i and was estimated using Bayesian statistics. The various faults and floating earthquake sources were assumed to be mutually independent statistically. The probability distribution of maximum PGA can be formally written as

$$F_{Ymax}(y;t)=\prod_{i=1}^{n} P[Ymax_i < y;t] \tag{5}$$

where $Ymax_i$ is for source i, Further simplification lead to

$$F_{Ymax}(y;t)=\exp(-\sum_{i=1}^{n}\mu_i tP[Y_i > y]) \tag{6}$$

where $P[Y_i > y]$ is the probability of exceedance of peak acceleration for source i, Given service life t and $1-F_{Ymax}(y,t)$ i.e. exceedance probability of PGA value y was estimated using eq. 6.

100 year PGA values for 0.5 exceedance probability obtained at various grid points were smoothened prior to contouring over a four times larger window, using a curve which has a weight 0.5 at central grid point and the remaining grid points have weights inversely proportional from the central grid point. In developing the SZM the countour map of PGA were taken as EPGA, and the acceleration response spectral value (5% damping spectra) for the periods in the range of 0.1 and 0.5 sec where averaged to obtain the values of seismic (acceleration) coefficients for demarcation of various seismic zones. Figure 7 shows the seismic zones, which follow more or less the 100 year PGA contours with islands and narrow seismic zones removed. The four seismic zones shown in figure 7 are at significant variance with the five seismic zones incorporated in 1970 SZM shown in figure 2. The five seismic zones in 1970 SZM have been incorporated on subjective estimate of EPGA from MM intensity in various parts of India derived from data of earthquake occurrence. SZM shown in figure 7 portray seismic zones with equal probabily of exceeding the recommended EPGA or seismic coeffieients (spectral accelerations), and removes the effect of stray earthquakes of high magnitude which are given greater significance in deterministic approach. The proposed SZM is not based on possible maximum MM intensity in various tectonic units but is based on the likely ground acceleration to be resisted by the structures in their service life (100 years). SZM shown in figure 7 incorporates a higher seismic status along western parts of Peninsular Sheild and continental shalf region, which forms a mobile belt in which sedimentary basins have developed during Tertiary, even though PGA contours do not show higher values.

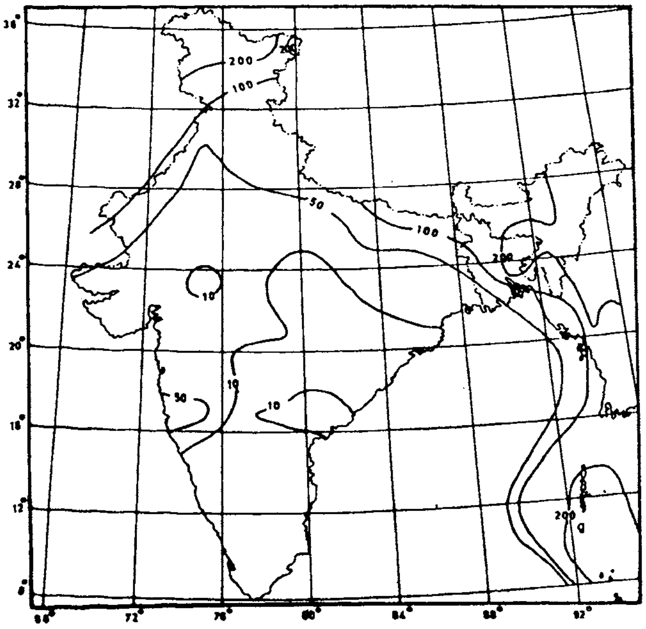

Figure 6. 100 Year Acceleration in cm/sec².

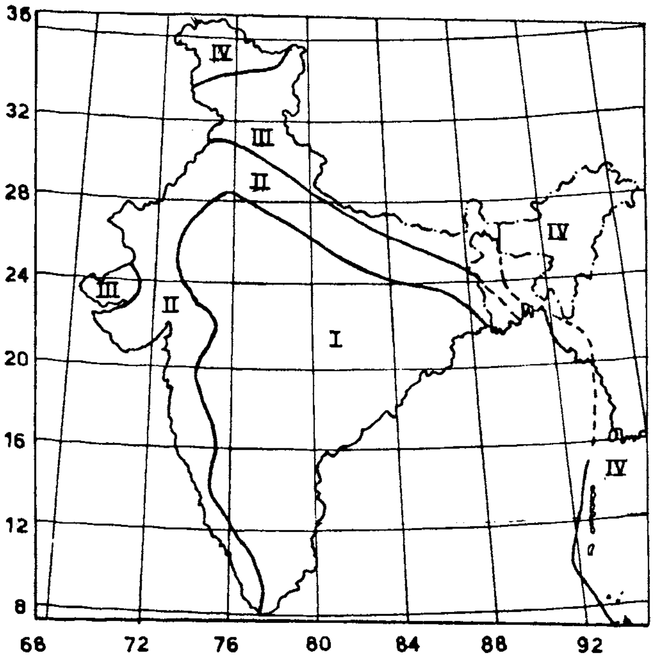

Figure 7. Proposed Seismic Zoning Map of India.

ndian Standard Criteria for Earthquake esistant Design of Structures (IS: 1893-1984) rescribe basic horizontal seismic coefficient nd seismic zone factor F_o for evaluation of eismic coefficients from average acceleration pectra (Fig. 8) for seismic zones shown in igure 2. Table I indicates the value of basic orizontal seismic coefficients and seismic one factors F_o for the four seismic zones ortrayed in SZM shown in figure 7.

able I : Recommended $_o$ and F_o for propsed four seismic zones shown in figure 7.

eismic Zone	$_o$	F_o
I	0.018g	0.08
II	0.032g	0.14
III	0.056g	0.25
IV	0.10g	0.45

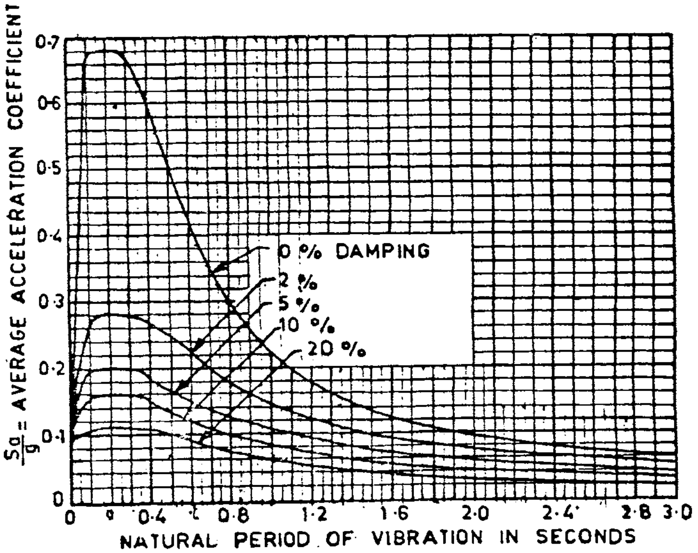

Figure 8. Average Acceleration Spectra (IS: 1893-1984).

SEISMIC DESIGN PARAMETERS FOR UNDERGROUND STRUCTURES

The Indian code (IS:1893-1984) specify seismic coefficients in terms of spectral acceleration representing dynamic response of the structures of various periods and damping. Underground structures, being completely surrounded by soil or rock mass follow closely the displacement of the ground. Srivastava (1988) suggested effective peak ground velocity and acceleration for the five seismic zones shown in figure 2 as given in table II.

Table II : EPGA and EPGV for the five seismic zones in 1970 SZM (Srivastava, 1988).

Seismic Zone	Effective Peak Ground Acceleration g	Effective peak Ground Velocity cm/sec
I	0.04	4.0
II	0.05	6.5
III	0.11	14.0
IV	0.14	18.0
V	0.22	28.0

The Indian Code recommends that for undergriund structures at 30 m depth or below, the design earthquake force may be taken as half of the value at the surface. No universally accepted law for variation of intensity of ground motion with depth has so far been worked out. It is desirable that for major underground project sites detailed investigations are carried out and seismic source zones are identified to work out earthquake motion for analysis and design. Table III, gives the effective peak ground velocity and acceleration recommended for adoption in the four seismic zones shown in the proposed SZM for estimation of maximum free feild strain and maximum curvature (distortion) in underground structures.

Table III : EPGA and EPGV for four seismic zones in proposed SZM recommended for design of underground structures.

Seismic Zone	Effective Peak Ground Acceleration g	Effective peak Ground Velocity cm/sec
I	0.04	4
II	0.08	10
III	0.14	18
IV	0.30	36

In addition to the effects of ground motion in the medium around underground openings, movements along major discontinuity surfaces (shear zone, etc.) or an active fault extending from the seismic rupture zone to the site cut accross underground structures, result in displacement and fracture of the lining and surrounding soil/rock mass. In general it is not feasible to design openings to restrain displacement along such active Tectonic features. In case this is not possible and the underground structure (e.g. a tunnel) has to cross an active fault, an estimate of seismic slip along the fault has to be made and measures for absorbing displacement through provision of appropriate flexibility to minimise damage should be adopted as well as means to facilitate repairs should be provided.

MOUNTAINOUS TERRAINS

Higher peak ground accelerations have been observed at hill tops with reference to that near valley base in mountainous terrains. This is the result of excitation of the hill ranges bordering deep gorges and canyons. The very shallow surficial deposits and scree material on valley slopes, in general do not cause further amplification of ground motion. To cater for such effects, as an alternative to rigorous analysis to work out the response of the hill range, The predicted EPGA could be taken at mid-canyon height and motion is worked out at different elevations of the valley for design of structures. For major structures (e.g. high dams) detailed analysis to work out the ground motion at the valley base and various elevations should invariably be carried out.

CONCLUSION

The SZM incorporated in the Indian code are based on subjective estimates of intensity from available information. A combined statistical and seismotectinic approach provide a more rational estimate of EPGA for preparation of SZM. Such a analysis for estimation of 100 year EPGA do not support delineation of five zones with equal exceedance probability and uniform ratio of seismic hazard among various zones. The proposed SZM (Fig. 7) is based on likely ground motion to be resisted by the structures in their service life. In mountainous terrains higher EPGA would occur along hill ranges and steep valley slopes forming deep gorges and canyons. The prescribed design values in such situations could be taken at mid-canyon hights. However a rigorous analysis to work out ground motion at sites of major structures (e.g., high dams) will be more appropriate. EPGA and EPGV have not been specified for design of underground structures and their values have been suggested for the various seismic zones in the proposed SZM.

It is emphasized that seismic zoning of a country is a continuous process depending on its gradual acceptance by users and improvments in the data base and analytical techniques for prediction of design ground motion.

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