Chapter 1
Smoothed and Normalized Design Spectrum for Indian Rock Sites

P. Anbazhagan, Ketan Bajaj, and M. Shimna

Abstract Seismic resistance design requires the estimation of futuristic seismic force to the structure in terms of spectral acceleration/velocity/displacement at the corresponding natural period of the structure. These expected seismic forces are defined based on detailed seismic hazard analysis and design spectrums from recorded earthquakes in the region. In this study, we have presented seismic design criteria in the Indian Seismic Code IS 1893 since its development, state-of-the-art procedure for the seismic hazard estimation, and the development of seismic design spectrum at the Indian Rock Site from North India and South India seismic data separately. The first Indian seismic code of IS 1893 was released in 1962 based on the studies of the Geological Survey of India on past earthquakes. IS 1893 was frequently revised soon after major earthquakes in different parts of the country and the currently available version is IS 1893 (2016). The seismic zonation map of India is based on past earthquake intensities and not on systematic futuristic seismic hazard estimation accounting for probable location and size of earthquakes. The different natural period of structural design requires respective design spectral amplitude. The previous versions of IS 1893 have given seismic coefficients for seismic zones and spectral amplitude for the different periods based on earthquakes recorded in US at an epicentral distances of 50–70 km, with multiplication factors. A recent version of IS 1893 adopted a design spectrum from the Uniform Building Code, again without considering regional data. After discussing these points, a modern smoothened, and normalized way of developing the design spectrum using regional data is explained. Further, rock site seismic records from the southern and northern parts of India were collated and used to create the design spectrum. The derived design spectra presented are applicable at the rock sites for 5% damping based on inter- and intraplate regions.

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Our study shows North and South Indian spectrums are different from the IS 1893 spectrum and the signature of each seismotectonic region is reflected in the proposed new spectral shape.

Keywords Seismicity · Seismic zone map · Seismic coefficient · Design spectrum · IS 1893

1.1 Introduction

India is rich in resources, culture, tradition, knowledge, and wisdom, which unfortunately are not truly reflected in the anti-seismic design and construction. Even today, the seismic code recommends seismic coefficient for the design of structure based on intensities and normalized spectrum arrived based on data recorded in US. On the other hand, the continuous tectonic strain buildup in the Himalayas causes several moderate and minor earthquakes, indicating the importance of Anti-Seismic Construction (ASC). Many ASC practices were traditionally adopted in several parts of India in the olden days and had slowly disappeared due to several reasons. The major reasons are an improper scientific explanation of those excellent practices, documentation, and lack of code of practice. Even now, simple rolling floor constructions above wooden beams in north Indian houses and sandbox techniques in temples in south India withstood several earthquakes. ASC might have been practiced from the experiences gained by our forefathers. These experiences might include two major aspects, one is past seismicity and expected future seismic force, and another is material and methods capable of handling expected seismic force. Later on, we can see via some rare current construction practices in the villages and age-old temples, but former ones are not available due to the unavailability of the historical scripts. At the same time, an increase in natural hazards, high population, and improper construction place India at high seismic risk and exposure at the global level [1]. Anti-seismic design and construction is a highly prioritized area to reduce seismic disasters. This is possible through proper estimation to provide reliable futuristic seismic forces for design in codes and make ASC a practice mandate. The former one is dealt with in this paper in detail to overcome some ambiguity in IS 1893-Indian Standard CRITERIA FOR EARTHQUAKE RESISTANT DESIGN OF STRUCTURES PART 1 GENERAL PROVISIONS AND BUILDINGS.

IS 1893 was first published in 1962 and revised soon after major earthquakes in the country, and the recent version was published in 2016. Seismic zones are marked based on past earthquake locations, zone factors are assigned based on past intensities, and design parameters are recommended based on the work in Western countries [2]. Indian seismic zonation maps and values are not based on a systematic estimation of potential hazards in each part of the country but are lumped values based on past known earthquakes [3]. The very first detailed seismic microzonation methodology was developed by the first author [4] by accounting geology, seismicity, seismotectonics, soil, site effects, and induced effects, a typical microzonation map of Bangalore was shown. But even today, we do not have a comprehensive futuristic seismic risk map of any city in India. Even though several seismic microzonation studies are carried out for Indian cities, the time taken for collating data and completing final maps makes these studies outdated. The seismic zonation map should be updated once in every 5 years or soon after a significant earthquake in the region, whichever is earlier. The current version of the IS 1893 seismic zonation map and design spectrum has several ambiguities and is not based on the state-of-the-art practice in the subject area; that could be the reason that the Sectional Committee mentions in every version of code that "there cannot be an entirely scientific basis for zoning in view of the scanty data available" and "Structures designed as per IS 1893 [5–11] are expected to sustain damage during strong earthquake ground shaking". So this study summarizes the development of seismic zone maps and seismic design coefficients in IS 1893 and highlights how to estimate futuristic seismic hazards at the bedrock level using rupture-based seismic hazard analysis developed at IISc [Indian Institute of Science].

This paper presents seismic records compiled by IISc for inter and intraplate regions of India, hereafter called South India and North India. Since both areas are entirely different regarding geology, seismicity, seismotectonic, and soil thickness and types, this is reflected in the seismic signatures, e.g., response spectrum. The complied acceleration time history data are separated based on region, and the cut-off periods for acceleration, velocity, and displacement-sensitive sections of the spectrum were estimated. Peak spectral acceleration, velocity, and displacement were estimated for the horizontal and vertical components for 5% damping at bedrock level. These results are further used to develop smoothened and normalized design spectrum for Peninsular India and North India. This is the first design spectrum of Peninsular India and North India using regional recorded earthquake acceleration time histories and state-of-the-art knowledge on the subject.

1.2 Indian Seismicity and Seismotectonic

India is rich in natural resources and aesthetic landscapes due to continuous seismotectonic and geological transformation, and these constant changes are non-uniform throughout the country. The degree and type of tectonic movement in different parts of India vary. Figure 1.1 shows the tectonic movements of India, which is part of Indo Australian Plate, moving with a speed of 26–36 mm/year in the Northeast direction and colliding with the Eurasian Plate, forming the Himalayan mountain ranges [12]. Indian landmass is predominately located on one side end of the Indo-Australian Plate [13]. Higher tectonic activities make this part to be called an Indian plate with unique understood seismotectonic activities. Shen [13] has highlighted that seismologists suspected from the 1980s that the Indo-Australian plate may be breaking up, ruptured four faults simultaneously within the Plate in April 2012 is a part of this breakup. One can narrow down the plate tectonic of India by taking effect of broadly distributed deformation of the northern Indian Ocean area within the composite India–Australia–Capricorn Plate. This area is well recognized as an Indian plate as a result of a reactivated fracture zone in the Indian Ocean Basin [13]. Jade et al. [14] showed that the "India plate borders the Eurasia plate on its northern and eastern boundary, Arabian plate on its western boundary; Somalia, Capricorn, and Australia plates to the south". Divergent boundary (pull apart) and associated deformation and activity are being documented with increased seismic activity in the Southern and Eastern boundary of the Indian plate. These south and southeastern and western boundaries may create large earthquakes resulting in Tsunamis affecting the Indian and Sri Lankan coastline and some associated moderate earthquakes in the landmass. So, special attention needs to be paid to understand these new seismic activities on the Indian Plate Southside as many nuclear power plants and harbors of India are located on the South Indian coastlines.

The major part of South India is located at mid of the Indian plate, which is a thin crust thickness. A major portion of it is called Peninsular India (PI) and is considered to be an intraplate region. The entire region is formed due to different geological transformations. Low plate thickness in the area causes rapid drifting towards the Himalayas in the northeastern direction with a high velocity of 5 cm per year [15]. Mohraz [16] interpreted that the earthquakes of the Indian plate interior are results of the periodic accumulation of stress/strain due to the shortening and release of accumulated strain along the same directions during the extension. This may be the reason that Central India has a fault plane at a depth of 5–38 km [17] and has caused significant earthquakes at Killari (Latur) and Jabalpur. Most of the intraplate earthquakes in PI are associated with unidentified local faults and weak zones. Jade et al. [14] highlighted that the Indian plate interior is moving as a rigid block with a velocity similar to the Indian plate velocity and found no significant strain accumulation based on GPS measurement and the localized regional deformation specific to the active dislocations and faults in the region causes intraplate earthquakes. This is the main reason for isolated PI seismic events from each other, the movement along the regional dislocations and faults [14]. The northwestern part of the Indian plate covers the western part of India, i.e., edge of PI. The broad west boundary of India is a triple junction region where plates of India–Arabia–Eurasia meets. According to [18], Bhuj 2001 earthquake seems to be of the diffused Indian Plate western boundary rather than of intraplate tectonics. The western boundary of the Indian plate close to Kachchh is an active and transformed boundary and is the reorganization of plate velocities and directions [19], which induced a change in the Arabia–India–Somalia triple junction. Freeman [19] highlighted the chances of infrequent earthquakes of magnitude 7 and greater along the Arabia–India plate boundary unless deformation is in the form of aseismic creep. This scenario makes complex straining of western Gujarat and causes frequent moderate seismic events. Moving north; covering west and eastern parts of the north of Indian plate is the Himalayan Arc of 2500 km and characterized by several thrust faults that sole into the basal detachment of the Himalayan wedge or the main Himalayan Thrust. This entire region is a convergent boundary with a non-uniform slip rate and strain-locking zones. The

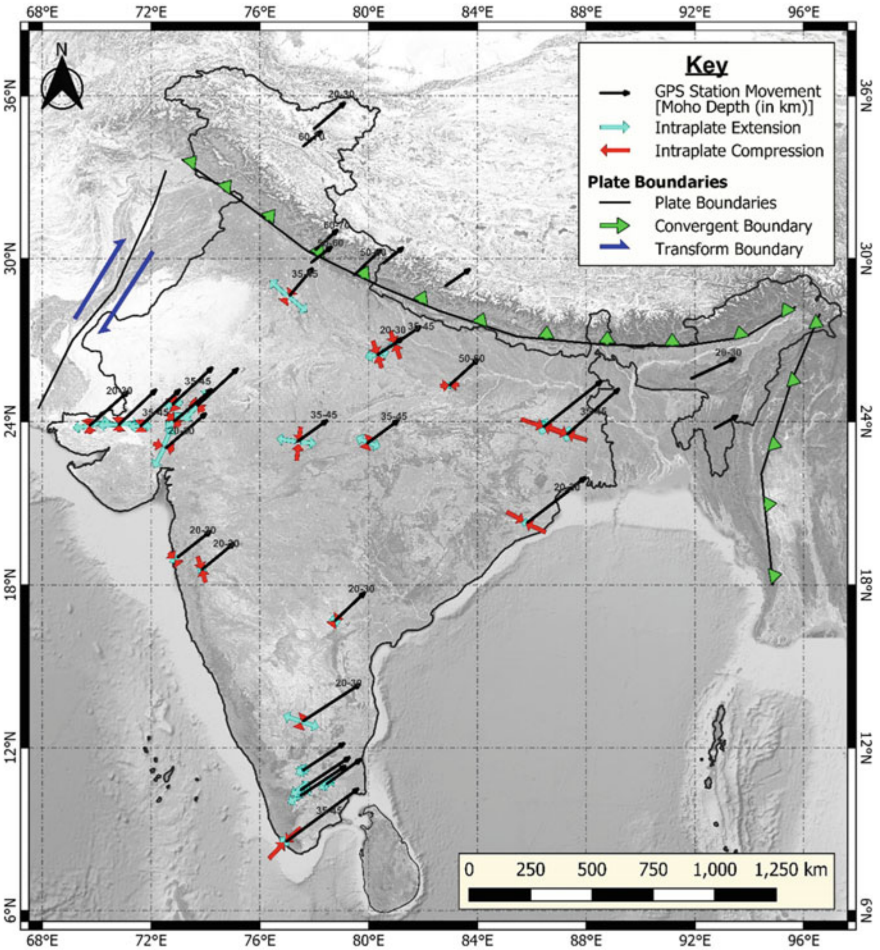

Fig. 1.1 Tectonic movements of India with Moho depth in km (marked in black long thin arrow) and stress direction of extension and compression (marked as a short thick arrow)

Himalayan Arc is seismically active due to the active under-thrusting of the Indian tectonic plate below the Eurasian plate and can be segmented from west to east into Kashmir, Ladakh, Gharwal, Kumaon, Nepal, Sikkim, Bhutan, Arunachal Himalaya, and Eastern Syntaxis [14]. We have recently estimated the futuristic seismic amplification of the Indo-Gangetic Plain, considering possible significant earthquakes due to the seismic gaps [20]. The eastern part of the Indian Plateau is much more complex, where three tectonic features of convergent and transformed boundaries and intraslab seismic activities take place. The northeastern side of the Indian plate, having transform motion with the Eurasian plate and the Eastern side with Burma–Sunda Plates. India–Burma convergence megathrust is currently accumulating strain and inactive/aseismic due to the lack of notable interplate instrumental earthquakes, which will eventually be released in future earthquakes [21]. There has been no big earthquake in the recent past in the northeastern part of India, but low to moderate events have caused extensive damages and liquefaction at several locations for a magnitude of 6 and less [22]. Overall, we can recognize that India has different seismic recurrences, seismotectonics, seismic sources, and depths. So, these may result in different seismic signatures and associated response spectrum even for the same site condition, i.e., layers with shear wave velocity (V_s) of more than 1500 m/s, which need to be incorporated in seismic design consideration in various parts of India.

1.3 Geology and Subsurface of India

Indian tectonic activities created a different type of surface and subsurface formation in India, where rock and soil layers are different in every kilometer grid of India. These variations are reflected in subsurface soil and soft rock type, thickness, and topography level. Subsurface layers causing Seismic Geo Hazards (SGH) of amplification, liquefaction, ground deformation, and landslide generally have V_s less than 1500 m/s and overlay hard rock, non-amplifying layer with V_s of 1500 m/s and above. Several earthquakes in India caused all types of SGH for a magnitude of 5.5 and above. But even now, there is no comprehensive SGH estimation using regional data and models. Researchers in India have made several attempts to estimate SGH and seismic microzonation maps since the work of [4]. But still, far away to estimate reliable SGH and microzonation maps using regional data and models. Here, we restrict our discussion only to the variation of surface and surface materials in the Indian landmass responsible for SGH. The shear strength of the subsurface layers in terms of standard Penetration Tests (SPT) N values or V_s values from geophysical tests are predominantly used for seismic site characterization and to estimate SGH at each place. Even though ample geotechnical data is generated as part of infrastructure projects, this data available for researchers is minimal. Even when the data is available, it is of little use since testing was not done as per the international standard requirement to use data for the estimation of SGH. In the last few years, shear wave velocity measurements have increased in different parts of India, and V_s is related to SPT N values [Uncorrected]. These correlations have different regression coefficients and goodness of fit within the region due to subsurface variation [23]. A couple of soil maps are published for India, but those are based on soil samples from very few centimeters with a concentration of geological classification. These surface-based soil maps may not help to arrive at a reliable SGH of any location. As per the author's knowledge, there is no comprehensive subsurface layer information required for SGH estimation.

In 2014, [2] reviewed geotechnical provisions in IS 1893 [10] and summarised soil type and its thickness in a different part of India using reliable data. Authors highlighted that "Geology and subsurface data collection show that India has diverse geology, soil and rock properties and site-specific variations in soil and rock properties must be accounted in seismic code similar to modern codes in foreign". It is worth mentioning that despite subsurface soil and rock variation in India, many researchers use SPT N or V_s seismic site classification developed based on American studies of NEHRP (National Earthquake Hazards Reduction Program) site classification [24]. NEHRP site classification is applicable for sites with rock depths 25–35 m and in shallow bedrock regions, it gives a higher site class and misunderstanding of amplification [25, 26]. At the same time, one should not forget that IGB has soil thickness up to 4–6 km deep with a very soft liquefiable surface soil deposit of up to 50 m. Systematic V_{ss} measurement up to a depth of 500 m and comparison with borelog by Anbazhagan and Ketan Bajaj [27] helped to understand the variation of amplification with depth in IGP. We found that amplification of subsurface layers several meters below the ground surface is much higher than that of surface layers, which needs to be accounted for in seismic design in those regions [20]. In principle, amplification correlations developed in other countries for peak ground acceleration/velocity and average spectral accelerations do not apply to India [25] and should not be used to site effect estimation. There is a need to understand the subsurface and surface geology and geotechnical properties and models for Indian soils at the micro-level and use them for reliable SGH estimation to reduce seismic risk due to SGH.

1.4 Regional Approach for Seismic Zonation Map

Several historic structures were designed for seismic forces and sustained several mega earthquakes in India. However, there is no evidence of a historical document explaining how it was done except for a few traditional practices in each state in the country. The seismic code initiative originated after a large-scale seismic disaster and destruction during Bihar–Nepal 1934 earthquake. The concept of seismic design was officiated only in 1962 in the IS 1893 seismic code. Buildings Sectional Committee [BSC] felt the need to rationalize the earthquake-resistant design of the structure to suit the Indian condition. BSC highlighted that IS 1893 [5] was based on accepted principles and practice in the field of earthquake-resistant design of structures before 1962. A number of important factors on the earthquake-resistant design of structures which are at the investigatory stage or not yet universally accepted were excluded from the IS 1893 [5] code and kept a scope for subsequent modification and revision. Many of the recommendations are primarily based on the research conducted abroad. Code clearly highlighted that it is not intended to lay down regulations such that no structure shall suffer any damage during earthquakes up all the magnitudes and the code, however, ensures that as far as possible, structures designed as per code are able to respond without structural damage to shocks of moderate intensities without total collapse to shocks of heavy intensities. Here, it is not clear to authors what moderate and heavy intensities of the different parts of India are. Only starting from IS 1893 [5] version, the earthquake-resistant design of normal structures and a detailed investigation were recommended for special and important structures. More or less above statements are repeated in most of the IS 1893 revised versions [6–11], and some of the statements are purposefully removed. Any seismic code recommendations can be broadly divided into three aspects; one is the recommendation of seismic hazard values at the bedrock level in the form of a seismic zonation map. Second is a recommendation of surface-level geohazard values based on different subsurface soil found in the region by considering site effects, liquefaction, and landslide. The third recommendation is building aspects such as configuration for earthquake resistance. This paper is limiting discussion only to the first and second recommendations in the IS 1893 code. The second one is not fully addressed in the code except few copied formulas and methods in the 2016 version without accounting for the testing practices and subsurface soil layers found in different parts of India.

Seismic zonation values are given in IS 1893 in the form of a map and the values in the table for each city for rock site conditions. IS 1893 [5] seismic zonation map was prepared using a rational approach based on the known magnitude and unknown epicenter. BSC assumed that all the other conditions were average and modified, such as average idealized isoseismal map in the light of tectonic, geology, and the maximum intensities as recorded from damage surveys, etc. The committee has also reviewed such maps in the light of past history and future possibilities and also attempted to draw a line demarcating the different zones to clear important towns, cities, and industrial areas; after making a special examination of such cases, *the little modification in the zone demarcations may mean the considerable difference to the economics of the project in that area.* These points in IS 1893 [5] clearly show that the seismic zonation map was prepared based on past intensities and economic development of the area. The seismic zonation map of 1962 was modified in 1966, the number of seismic zone in the country kept similar, but the boundary of zones was modified. Figure 1.2 shows the comparison of the seismic zonation map released in 1962 and 1966 in IS 1893. A summary of seismic coefficients for cities with populations above 20 lakhs as per the 2011 census is given in Table 1.1. The seismic coefficient specified in the IS 1893 [5, 6] corresponds to the maximum acceleration that may be expected in any direction. At the same time, BSC said that seismic coefficient/factors are dependent on many variables and factors, and it is an extremely difficult task to determine the correct seismic acceleration at each location in the country. Hence, seismic coefficients are broadly adopted in different country zones, and rigorous analysis is recommended for important projects. These two codes give seismic coefficients [the ratio of the design acceleration due to the earthquake and the acceleration due to the gravity] for different subsurface layers broadly classified into three types. Table 1.2 shows subsurface layers of three types defined in IS 1893 by taking bearing capacity and SPT N value as a reference as per IS 2131. These subsurface layers should not settle appreciably due to the vibration loading for a few seconds. This means that IS 1893 design parameters are unsuitable for the site that undergoes displacement or settlement due to vibration loading. Figure 1.2 shows that few parts of the country are under seismic zone 0 since there are no intensities in that region. In Table 1.1, we can see that many south Indian cities have zero seismic coefficients as per IS 1893 [5, 6]. Unfortunately, several damaging earthquakes have occurred in the 0 zones of the country, leading to the removal of 0 zones and updating the 1966 zone in 1970.

The first time, BSC felt that no place in the country was free from the earthquake, so zero was removed, and zones VI and V were merged as zone V. So, in 1970, IS

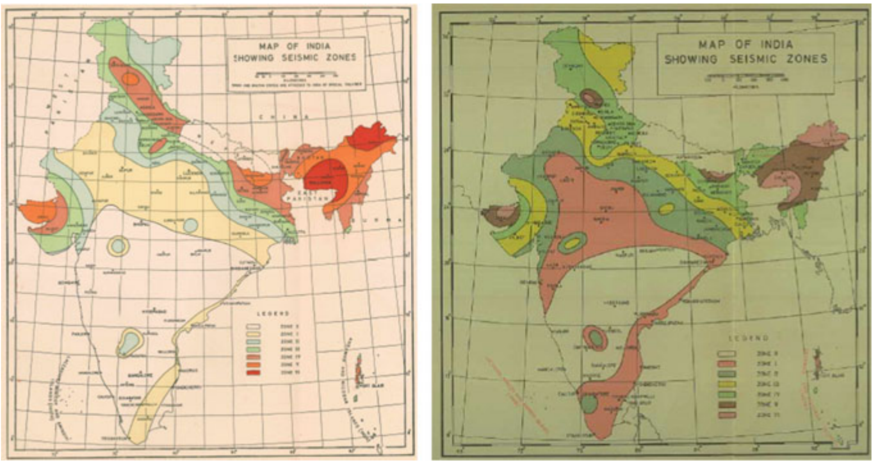

Fig. 1.2 IS 1893 seismic zonation maps published by Indian Standards Institution (IS 1893 [5, 6])

Table 1.1 Seismic coefficient/zone factor of cities with populations more than 20 lakhs as per 2011 census. The type of subsurface [T-I, T-II and T-III] is explained in Table 1.2

Sl no	Zonation year	1962			1966			1970/1975/1984		2002/2016
	Cities	T-I	T-II	T-III	T-I	T-II	T-III	T-I	Zone factor	Zone factor
1	Mumbai	0	0	0	0	0.01	0.02	0.04	0.2	0.16
2	Delhi	0.04	0.05	0.06	0.05	0.06	0.08	0.05	0.25	0.24
3	Bangalore	0	0	0	0	0	0	0.01	0.05	0.10
4	Hyderabad	0	0	0	0	0	0	0.01	0.05	0.10
5	Ahmedabad	–	–	–	0.04	0.05	0.06	0.04	0.2	0.16
6	Chennai	0	0.01	0.02	0	0.01	0.02	0.02	0.1	0.16
7	Kolkata	0.04	0.05	0.06	0.04	0.05	0.06	0.04	0.2	0.16
8	Surat	0.02	0.03	0.04	0.02	0.03	0.04	0.04	0.2	0.16
9	Pune	0	0	0	0	0.01	0.02	0.04	0.2	0.16
10	Jaipur	0	0.01	0.02	0	0.01	0.02	0.02	0.1	0.10
11	Lucknow	0	0.01	0.02	0.02	0.03	0.04	0.04	0.2	0.16
12	Kanpur	0	0.01	0.02	0.02	0.03	0.03	0.04	0.2	0.16
13	Nagpur	0	0	0	0	0	0	0.02	0.1	0.10

Table 1.2 Subsurface classification as per IS 1893 different versions [5–11]

Code year	Type I	Type II	Type III
1962	Hard soil having a bearing capacity greater than 45 tonnes/m^2	Average style having a bearing capacity greater than 20 tonnes/m^2 and equal or less than 45 tonnes/m^2	Soft soil having a bearing capacity greater than 10 tonnes/m^2 and equal or less than 20 tonnes/m^2
1966	Soil Type I having a bearing capacity greater than 45 tonnes/m^2	Soil Type II having a bearing capacity greater than 20 tonnes/m^2 and equal or less than 45 tonnes/m^2	Soil Type III having a bearing capacity greater than 10 tonnes/m^2 and equal or less than 20 tonnes/m^2 provided that the standard penetration value (see IS2131-1963) is equal to or greater than 10
1970 1975 1984 2002	Type I rock or hard soil: well-graded gravel and sand gravel mixtures with or without clay binder, clayey sands, poorly graded, or sand–clay mixtures (GB, CW, SB, SW, and SC)* having N above 30	Type II medium soils—All soils with N between 10 and 30, and poorly graded sands or gravelly sands with little or no fines (SP*) with N > 15	Type III soft soils: all soil other than SP* with N < 10
2016	Type A rock or hard soil: well-graded gravel (GW) or well-graded sand (SW) both less than 5% passing 75 mm sieve (fines) Well-graded gravel—sand mixture with or without fines (GW-SW) Poorly-graded sand (SP) or Clayey sand (SC) all having N above 30 Stiff to hard clays having N above 30	Type B medium or stiff soils—Poorly graded sands or poorly graded sands with gravel (SP) with little or no fines having N between 10 and 30 Stiff to medium stiff fine-grained soils, like silts of low compressibility (ML) or clays of low compressibility (CL) having N between 10 and 30	Type C soft soils: all soft soils other than SP with N < 10. The various possible soils are: Silts of intermediate compressibility (MI); Silts of high compressibility (MH); Clays of intermediate compressibility (CI); Clays of high compressibility (CH); Silts and clays of intermediate to high compressibility (MI-MH or CI-CH); Silt with clay of intermediate compressibility (MI-CI); and Silt with clay of high compressibility (MH-CH)

Note N is the standard penetration value- Measured as per IS2131-1963/1981 method for standard penetration test for soil. *See IS1498-1959/1970 classification and identification of soil for general engineering purposes. In 2002 and 2016 versions of IS 1893 were given N as corrected N values code had only five seismic zones, and the seismic coefficient for different subsurface layers was given as a function of foundation type, i.e., "β for different soil foundation systems". For regular isolated footing, β is 1.0 for type I, 1.2 for type II, and 1.5 for Type III (see Table 1.2 for types of soil in the 1970 version). In the 1975 and 1984 versions, seismic coefficient method and response spectrum method factors are included. The latter factor is called a seismic zonation factor [Sa/g], and it is five times larger than the seismic coefficient as per IS 1893 [8, 9]. Not many changes were taken place in the later revision of IS 1893 [8] and 1984 when compared to the 1970 version. Three subsurface classifications given in the 1970, 1975, and 1984 versions of IS 1893 are almost similar and only desirable field N values are given with the updated version of IS 2131 and IS 1498. After sequence earthquakes at Latur (1993), Jabalpur (1997), and Bhuj (2001), IS 1893 was revised in 2002. Figure 1.3 shows the seismic zonation map of IS 1893 published in 1984 and 2016. The low seismic zone of I is completely removed, and several parts of the country are upgraded to higher zones. IS 1893 [10, 11] gives a zone factor for the Maximum Considered Earthquake [MCE], and a multiplication factor of ½ is suggested for Design Basis Earthquake to reduce MCE. Design seismic coefficient and zonation factor in seismic zonation maps from 1962 to the recent version of 2016 (see Table 1.1) are based on past earthquake locations and intensities reported in several parts of the country. The above discussion clearly shows that the seismic zonation map did not account for strain accumulation, the possible future seismicity, and systematic, rigorous seismic hazard analysis.

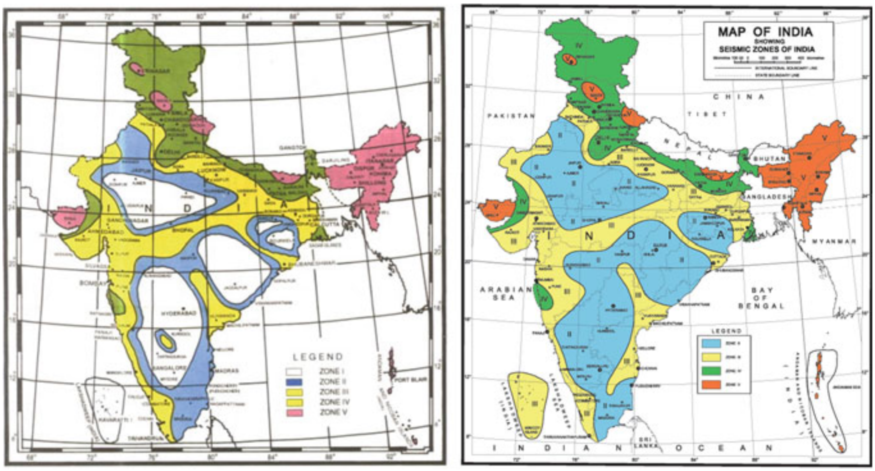

Fig. 1.3 IS 1893 seismic zonation maps published by Indian Standards Institution (IS 1893 [7, 11])

1.4.1 Regional Seismic Hazard Analysis

By knowing the seismotectonic and seismicity of India, uniform seismic zoning may lead to errors in arriving at the futuristic seismic zonation values. A study of IS 1893's different versions of codes clearly shows that the Indian seismic zonation map was not prepared based on the local variation of seismic aspects and state-of-the-art knowledge on the subject. Several seismic hazard analyses are carried out for cities in India or as a whole country, but the methodology and model adopted are almost similar. Some of the studies used outdated data and models. There are a lot of improvements have taken place in the seismic hazard analysis by accounting for regional seismicity and seismotectonic. These are yet to be systematically adopted by Indian researchers working in seismic hazard analysis. Even very critical structures and facilities in the country are designed using outdated analysis methods and results. As per the first author that many Indian researchers conduct seismic hazard analysis by adopting foreign procedures and models and are not doing any research to improve the same. Research carried out by the first author team reveals that a regional-specific approach is required to estimate reliably futuristic seismic factor estimation. Some interesting findings by accounting for regional seismic aspects in seismic hazard analysis can be found in [28]. We believe that seismic hazard analysis of the region should account for the following specific to the area.

- Identification of Seismic Study Area (SSA)—Area around the study area where earthquake occurrence in SSA and cause desirable ground motion at the study area.
- Location-specific Homogenization and magnitude conversion equation.
- Region-specific declustering approach.
- Maximum magnitude estimation considering regional rupture character [29].
- Selection of attenuation equations suitable to the region based on recorded earthquake data or intensity values and arrive ranks and weights of each attenuation equation for hazard estimation.
- Identification of probable potential future earthquake source locations in SSA by taking account of damaging earthquakes and strain released in the SSA.

Conventional deterministic and probabilistic-based seismic hazard analysis (SHA) give more weight to the location where earthquakes have occurred in the recent past. Also, they consider it a source in SHA, if the source has experienced an earthquake magnitude of 3.0 or above. This means conventional analyses give more seismic hazard values in a location where earthquakes have already occurred irrespective of the particular earthquake return period or repetition. The same concept was adopted in IS 1893 for assigning zone seismic coefficient/factor in all code versions. That may be the reason that seismic zones in the code are being modified soon after damaging earthquakes in the country. In order to overcome these issues, Anbazhagan et al. [30] developed rupture-based seismic hazard analysis by taking into account probable future earthquake locations. Anbazhagan and Silas Abraham [31] carried out Region-Specific Seismic Hazard Analysis of the Dam site by updating the procedure given by Anbazhagan et al. [30]. We believe that systematic region-specific seismic hazard analysis considering rupture character can help to arrive at reliable futurist seismic hazard values. The systematic region-specific hazard analysis steps are presented below:

(1) Selection of SSA based on Intensity/Damage Distribution/PGA interest to Structures (0.01 g) map.
(2) Identification of best magnitude conversion equations and Homogenization.
(3) Preparation of seismotectonic source map based on the regional data and seismic activity.
(4) Understand seismic distribution and delineation region for estimation of M_{max} and Recurrence relation.
(5) Estimation M_{max} for each source or region considering regional rapture character.
(6) Identification of Probable future rupture's location based on Anbazhagan and Silas Abraham [31].
(7) Characterize set of M_{max} and hypocentral distance based on regional seismotectonic considering damaging earthquakes in SSA in the last 50 years and Probable future rupture location as per (6).
(8) Selection of predictive relations, estimate weights, and ranks considering regional seismic data.
(9) Estimated PGA at the site for different combinations and identify controlling earthquake magnitude and distance resulting in higher PGA values. Deterministic RBSHA (RSHA-D).
(10) Probabilistic RBSHA (RSHA-P): Steps 1–8 remain the same. Some modifications in Deaggregation.
(11) Give more weightage to Probable Future Rupture Location by altering Deaggregation [20].
(12) Weights of the different models in the probabilistic logic tree are systemically estimated by considering the data support index in the RSHA-P.
(13) Map bedrock hazard and recommend design seismic coefficients or factors.

Considering differences in seismicity and seismotectonic throughout India, a region-specific approach could help to arrive at reliable futuristic seismic hazards in each section of India.

1.5 Soil Consideration and Design Spectrum

In general, seismic zones do not exclusively include site effects and induced effects of the earthquake, but emphasis on accounting for the same was spelt in the IS 1893 first version onwards. Site effects include wave modifications due to soil and topographic effects. The induced effects include ground deformation, liquefaction, and landslides. IS 1893 BSC stated that the intensity of shock greatly varies locally due to variations in the soil conditions. It is not possible to lay down the actual variations with present knowledge for different types of soils in quantitative terms. IS 1893 [5] and later version specifies that “design acceleration for the structure standing on the soil which will not settle appreciably due to the vibration lasting for a few seconds”. Any soil subsurface that undergoes settlement during dynamic loading should be improved and, after achieving no settlement layer, then use code acceleration. Subsurface layers are divided into three types [hard, average, and soft soils] for estimating site effects. IS 1893 [5, 6] codes classified the soil based on the Bearing Capacity (BC) (see Table 1.2). Since no reference was given on how to estimate BC, we can reasonably assume that BC is based on soil strength of cohesion and angle of internal friction, as the settlement of these soil is considered to be negligible. Criteria on zero settlement were kept unchanged, and the definition of soil types was updated in the 1970–2002 version with errors in soil classification [2]. Error in soil classification was corrected in the 2016 version of IS 1893, and field SPT N value correction was introduced in the recent version. However, it can be noted here that SPT N values corrections are suggested without accounting for differences in SPT practices in different parts of the country and using foreign-developed correction factors. Diverse SPT equipment and operator practices in the country result in a change in SPT N values from 15 to 85% of measured field N values, which was not exclusively accounted for in the SPT code of IS 2131 and simply given in IS 1893 [11]. Table 1.2 shows that Type III/C or soft soils are defined as soils where SPT N values are less than 10 and are intermediate to highly compressible; these materials may undergo ground deformation and settlement during vibration shaking. We can see from IS 1893 that a few efforts have been made to address local site-specific effects in seismic design, but classification and associated recommendations are far from the modern knowledge and findings in the country, and most of them are copied from foreign literature. Unless we properly integrate region-specific hazard values and site-specific effects as per state-of-the-art knowledge, it may be difficult to achieve zero damage structure even for futuristic moderate seismic events similar to developed countries. The occurrence of earthquakes of magnitude 6.5 or less is just news in developed countries, but it will be a disaster in India.

According to this study, the maximum or average horizontal peak acceleration for 5% damping at rock site conditions from deterministic SHA or probabilistic SHA (for 10% or 2% probability of exceedance in period structures (in general 50 years)) is shown as contours values in the country seismic zonation map. Then design spectrum periods of a structure are suggested for different damping levels and various soil sites found in the region based on locally recorded earthquakes and site-specific soil models. But the Indian seismic zonation map gives seismic coefficient or zonation factor based on past earthquake intensities and response spectrum developed based on US data. IS 1893 has given different seismic coefficients for three types of the subsurface in the 1962 and 1966 versions, and a multiplication factor by taking foundation types in the 1970, 1975, and 1984 versions [see Table 1.1]. In all these versions, average acceleration spectrum curves developed by Dr. Housner and others from four California earthquakes with N [multiplication factor to get the proper values of spectrum quantities] were suggested throughout the country. It can be noted here that these earthquakes were recorded at the epicentral distance of 50–70 km and magnitude of 6.5–7.7. Average acceleration spectrum curves are given for damping values of 0, 2, 5, 10, 20, and 40%. During 1962 and 1966, the period of the spectrum was 0.2–2.8 s, zoomed Y-axis in 1970 with peak horizontal value from 0.2 to 0.4 s with all damping values. In 1975, 0 and 40% damping curves were removed, and the average acceleration spectrum was given up to 3.0 s, and the initial portion [0.1–0.3] curves are horizontal, the rest of them remain the same. Figure 1.4 shows the average acceleration spectrum given in IS 1893. In the 1984 version, the code suggested only zone factor and average acceleration spectrum as Sa/g as Y-axis and period of zero to 3 s in X-axis for damping values of 0, 2, 5, 10, and 20%. These curves initially increase in slope, then become horizontal and followed by curves (see Fig. 1.4). These curves for maximum horizontal components of ground motions and for vertical motions, the half value of these curves were recommended in IS 1893 [5–9] versions. IS 1893 [10, 11] has given a design spectrum [Sa/g versus period] for 5% damping and three curves for three subsurface materials. The seismic coefficient and multiplication factor for different soil types are removed. The difference in spectral acceleration coefficient is shown only after 0.4 s, and soil types II and III have more spectral coefficients than type I [see Table 1.2] after 0.67 s and up to 4.0 s. These versions are also given an equation to arrive Sa/g for the different periods and suggested 2/3 horizontal spectrum should be considered as a vertical spectrum. It can be noted that in the 2016 version of IS 1893, spectra were given up to 6 s, and constant values were suggested from 4 to 6 s. Also, the 2016 version of IS 1893 gives separate spectra for equivalent static method and response spectrum method in Sa/g variation up to 0.1 s, i.e., short period. The average acceleration/ response spectrum given in IS 1893 (a different version) is not directly comparable except for repeated ones. Figure 1.4 shows the comparison of all spectrums for rock site 5% damping. IS 1893, 1975 and 1984 versions are given lower S_a/g coefficient with a multiplication factor, which gives lower design values when compared to later versions. So we divided the curves by 0.2 values to get normalized value without multiplication factor replaced as IS 1893 (1975/1984)-C. This also confirms that S_a/g is much lower than the 2002 and 2016 versions of the same code. Further spectrum is given in different versions of IS 1893 based on acceleration time history and not account for velocity and displacement time of data, i.e., medium and longer period codal values are much lower than the actual value of the seismic event.

Code has clearly given the source of the average acceleration spectrum curves up to the 1984 version, but later design spectrum source information is not explicitly provided in IS 1893 [10, 11] version. The study by the authors reveals that the Design spectrum given in the 2002 and 2016 versions may be adopted from UBC Uniform Building Code [31]. In UBC, the effects of local soil conditions are accounted through foundation factor F and site factor S where. S is related to four subsurface layers with thickness. These were arrived based on the work of [33]. We can note here that most of the modern code gives peak ground acceleration (PGA) for rock sites and site amplification factors for different soil sites at all periods. In particular, zero spectral acceleration [ZSA] for rock and soil sites is different, which is not implemented in the Indian code spectrum; up to 0.4 s of the spectral period, rock and different soil

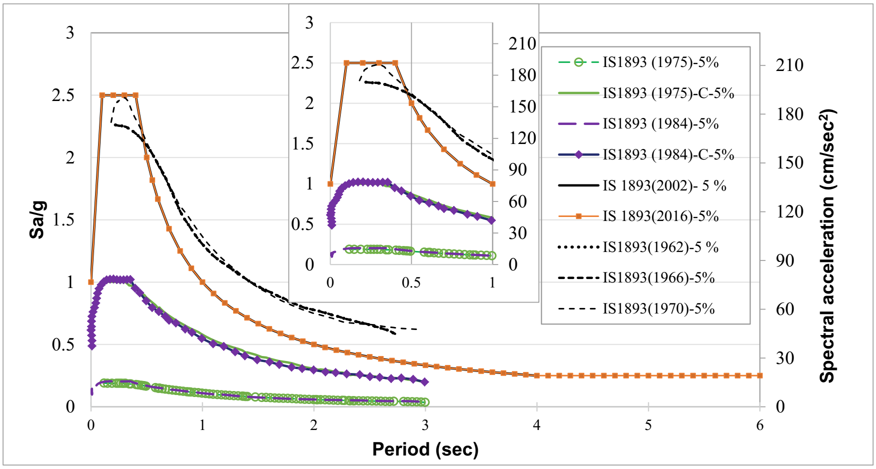

Fig. 1.4 Average acceleration spectrum curves and response spectra at rock site presented in IS 1893 from 1962 to 2016

sites have the same spectral amplitude. Several site response spectra were developed in India using measured data or site response analysis. Many of them are directly compared with the Indian code average response/ design spectrum.

1.6 Response and Design Spectrum

Any earthquake produces different types of seismic waves, which are recorded in seismometers in the form of velocity or acceleration with time. These time history data are recorded in two horizontal and one vertical components, and generally, one of the maximum horizontal components is used to arrive required time-domain parameters of peak ground acceleration/velocity/displacement (PGA/PGV/PGD) and durations of the events. Depending on the recording station, data can be classified as rock or different soil sites and further used for design parameter estimation. The vibration signal produces maximum acceleration or velocity or displacement and is depending on the frequency of the signal. As different stiffness and height of structure can have different natural periods/frequencies, if the natural frequency of the structure system matches with vibration maximum response frequency; then it can be subject to respective maximum acceleration or velocity or displacement. In general, short period [high frequency] is sensitive to acceleration, the intermediate period [medium frequency] is sensitive to velocity, and the long period [low frequency] is sensitive to displacement. So, it is necessary to characterize which frequency or period range that can produce maximum acceleration or velocity or displacement of recorded seismic signal in the region. These three regions are called acceleration-sensitive, velocity-sensitive, and displacement-sensitive regions of seismic events. Depending on the structure's natural period, respective acceleration or velocity or displacement should be considered in the design. So, any seismic design provision should reflect the same from regional seismic records.

A seismic zone map should give a variation of ZSA/PGA as a map in the region and give normalized and smoothed spectral shape by taking three sensitive regions and respective amplitude modification with the respective [PGA/PGV/PGD] normalized value. Rigorous and reliable SHA by accounting for all futuristic seismotectonic event possibilities can help to create a representative ZSA/PGA map. Seismic data recorded in the region at rock and different soil site stations can help to produce normalized and smoothed spectral shapes showing maximum amplitude and cut period of acceleration, velocity, and displacement in the region. Response spectrum is defined as the maximum relative linear response of a single degree of freedom system (SDOF) for excitation by a given strong earthquake seismic ground motion [34, 35]. Initially, Biot [36] introduced the concept of response spectra and proposed the standard spectral shape for earthquake-resistant design of the building. Housner [37, 38] averaged and smoothed the response spectra considering the four strong-motion records and proposed using average spectrum shape in earthquake engineering design. Newmark and Hall [39, 40] recommended a smooth response spectrum concentrating on three regions viz. acceleration (short period), velocity (medium period), and displacement (long period). The shape of Biot, Housner, Newmark, and Reg. Guide 1.60 spectra [41] were fixed by averaging the spectral shape with respect to the site conditions, distance, and earthquake size (magnitude or intensity). Various researchers (e.g., [42–44]) contributed towards the development of the Newmark–Hall spectrum. Mallick et al. [45] determined the amplification factors for acceleration, velocity, and displacement-sensitive regions of the spectrum for various damping values. Mallick et al. [45] showed that the displacement amplification factor is significantly different as compared to the previous studies. Malhotra [46] proposed a methodology to compute elastic response spectra for incompatible acceleration, velocity, and displacement time histories to account for all maximum possible responses. The procedure recommended by Malhotra [45, 46] for deriving the normalized response spectra is used here to develop the design spectrum of South India and North India.

1.6.1 Acceleration Time History to Design Spectrum

India is improving seismic instrumentation, and right now, 150 seismic stations are installed in different parts of the country and are being continuously monitored [47]. Here we have taken typical Indian data to explain how recorded acceleration data is converted as a response and design spectrum. An earthquake can have an acceleration time history along three components. Typical rock site record of NI earthquake data is shown in Fig. 1.5a. In this, the maximum acceleration time history is the NS component, which is used to compute velocity and displacement time history, as shown in Fig. 1.5b. These data are further used to arrive at a 5% damped acceleration, velocity, and displacement spectrum, as shown in Fig. 1.5c. These three responses are normalized with respect to maximum quantities, i.e., PGA, PGV, and PGD. Here, we can see that maximum acceleration response up to period of 0.92 s, maximum velocity response up to the period of 2.32 s, and the rest are maximum displacements. These values change with earthquake data, so compiling larger data will provide reliable values. Malhotra [46] and Mallick et al. [45] explained the procedure for deriving the normalized response spectra by solving a dynamic equilibrium for the single-degree-of-freedom equation. In-house MATLAB code has been used to solve Eq. 1.1 as per [45, 46] for a given acceleration, velocity, and displacement time history.

The spectral displacement (*SD*) is the maximum displacement of the SDOF system at any time, likewise the spectral velocity and spectral acceleration.

$$SD = |u|_{max} \tag{1.1}$$

Using the above equation, the spectral acceleration (*SA*) approaches to PGA at a short period, and spectral displacement approaches to PGD. The equation that relates *SA*, *SD*, and spectral velocity (*SV*) is as follows:

$$SA\left(\frac{T}{2\pi}\right)^2 = SD = SV\left(\frac{T}{2\pi}\right) \tag{1.2}$$

Further, the *SD* obtained from Eq. 1.1, has been converted to *SA* to obtain the tripartite response spectrum. The tripartite response spectra have been normalized as follows: firstly the central period (T_{cg}) of the seismic ground motion is calculated as

$$T_{cg} = 2\pi\sqrt{\frac{PGD}{PGA}} \tag{1.3}$$

This T_{cg} causes a horizontal shift in the response spectra, PGA and PGD change to $PGA \times T_{cg}/2\pi$ and $PGD \times 2\pi/T_{cg}$ respectively, however, PGV remains constant. Further, PGV and SV are normalized with respect to $\sqrt{PGA.PGD}$, this makes PGA and PGD unity and PGV and SV to make the following non-dimensional form

$$\overline{PGV} = \frac{PGV}{\sqrt{PGA.PGD}} \tag{1.4}$$

$$\overline{SV} = \frac{SV}{\sqrt{PGA.PGD}} \tag{1.5}$$

Further, the normalized spectrum has been smoothened considering the least-squares fitting of straight-line segments through the median curve. A typical smoothened median response spectrum is given in Fig. 1.6. The amplification factors above unity corresponding to acceleration, velocity, and displacement are denoted as α_A, α_V, and α_D. T_1, T_2, T_3, T_4, T_5, and T_6 in Fig. 1.6 are control periods (where

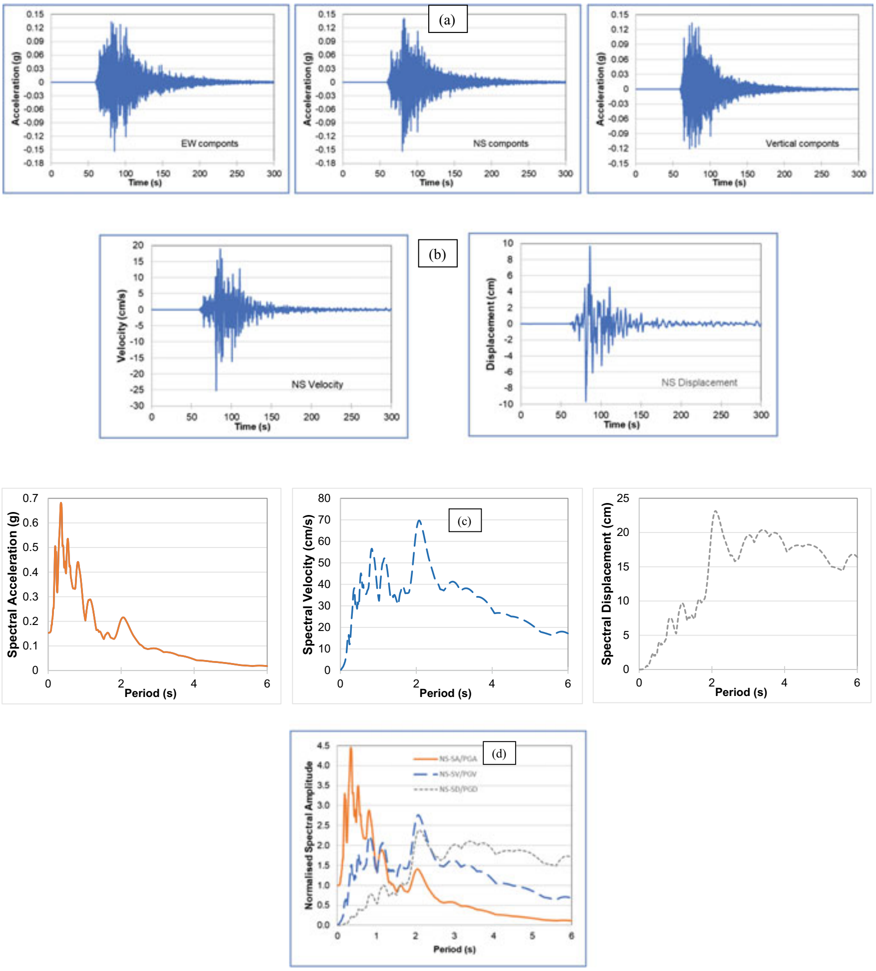

Fig. 1.5 Typical rock site earthquake time history and response spectrum **a** Acceleration time history of EW, NS, and Vertical record, **b** Maximum (NS) Velocity and Displacement time history data, **c** Response spectrum for acceleration, velocity, and displacement data and **d** Normalised spectral amplitude of acceleration, velocity, and displacement with respective peak values

the straight-line segments meet). A typical example of obtaining a normalized tripartite plot of 2011, Sikkim earthquake (6.9 M_w) recorded at a hypocentral distance of 102 km is given in Fig. 1.7. The recorded PGA, PGV, and PGD are 0.131 g, 0.025 m/s, and 0.002 m, respectively. Acceleration, velocity, and displacement time history are shown in Fig. 1.7a used for deriving the SD using MATLAB. Further, SD is converted to SV and a tripartite plot of 5% damping response spectrum is given in Fig. 1.7b. Using Eqs. 1.3, 1.4 and 1.5, the developed response spectrum is normalized and given as Fig. 1.7c. The whole procedure is further used for deriving the normalized site response spectrum for the deep and shallow bedrock sites of IGB and SI.

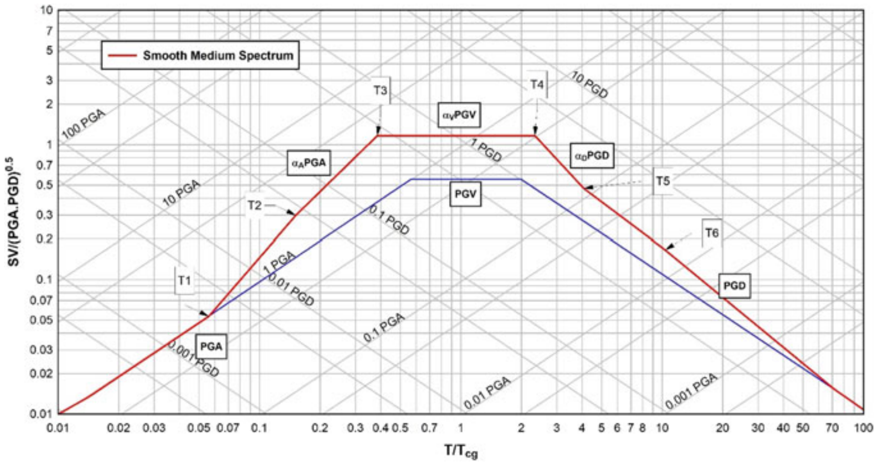

Fig. 1.6 Typical smooth medium response-spectrum considering PGA, PGV and PGD

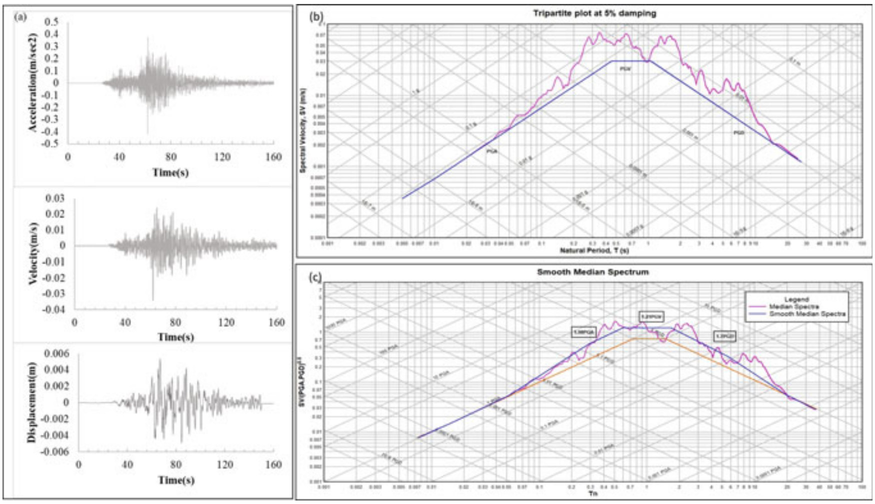

Fig. 1.7 Typical acceleration, velocity, and displacement time history on the left side (**a**), respective 5% damping response spectrum (**b**), and final smooth normalized response spectrum (**c**)

1.6.2 Cut-Off Period for Acceleration, Velocity, and Displacement

Cut-off period of acceleration, velocity, and displacement, a part of the design spectrum where the maximum response of respective quantities are represented, is the function of source, path, and site characters. These values in IS 1893 were adopted from UBC irrespective of Indian seismicity, path attenuation, and site geology in India. Even in modern codes, these cut-off regions are not well defined using a tripartite plot of seismic data from the region. Hall et al. [48], Malhotra [45] and Mohraz [42] defined the different period of the design spectrum that is sensitive to PGA, PGV, and PGD. Hall et al. [48] and Mohraz [42] assumed that SAs for periods 0.33 s, 0.33, and 3.33 s, and more than 3.33 s are sensitive to PGA, PGV, and PGD. Malhotra [45] showed that SAs for a period up to 0.62 s, 0.62–2.6 s, and the rest correlated well with PGA, PGV, and PGD for the same data. Malhotra [45] concluded that cut-off periods could change for different sets of seismic ground motions and need to be incorporated into the design spectrum. Hence, in this study, the PGA-, PGV-, and PGD-sensitive regions for NI and SI, correlation of SA at various periods with PGA, PGV, and PGD has been plotted. The recorded bedrock seismic ground motion data for the Himalayan region and Stable continental region has been used to determine the cut-off periods for PGA-, PGV-, and PGD-sensitive regions.

Figure 1.8 shows the correlation of SA with PGA, PGV, and PGD for NI and SI for rock sites with 5% damping. From Fig. 1.8, it can be noted that SA for the period up to 0.38 s and 0.30 s is correlating well with PGA for NI and SI, respectively. Further, for the period between 0.38 and 2.28 s, SA correlates well with PGV, and the rest correlates best with PGD for NI rock sites. Similarly, in the case of SI, SA correlates best with PGV for the period between 0.30 s and 1.55 s and above 1.55 s with PGD for rock sites. Bureau of Indian Standard (IS:1893 [11]) defined the cut-off period for rock sites as 0.1 and 0.4 s, which is significantly different from the present study. Similarly, it is noted here that the cut-off period calculated in this study is considerably different from [48, 42]. Hence, the methodology used in this study does not make any prior assumption in determining the cut-off period for three sections of the design spectrum.

1.7 Smoothed and Normalized Spectrum from India

Even though recorded time history data availability is very limited in India for engineers to understand earthquake effects, the first author continuously uses available data to bring Indian-specific seismic studies required for the seismic design in India. The first author and team are continuously trying to solve some of India's engineering

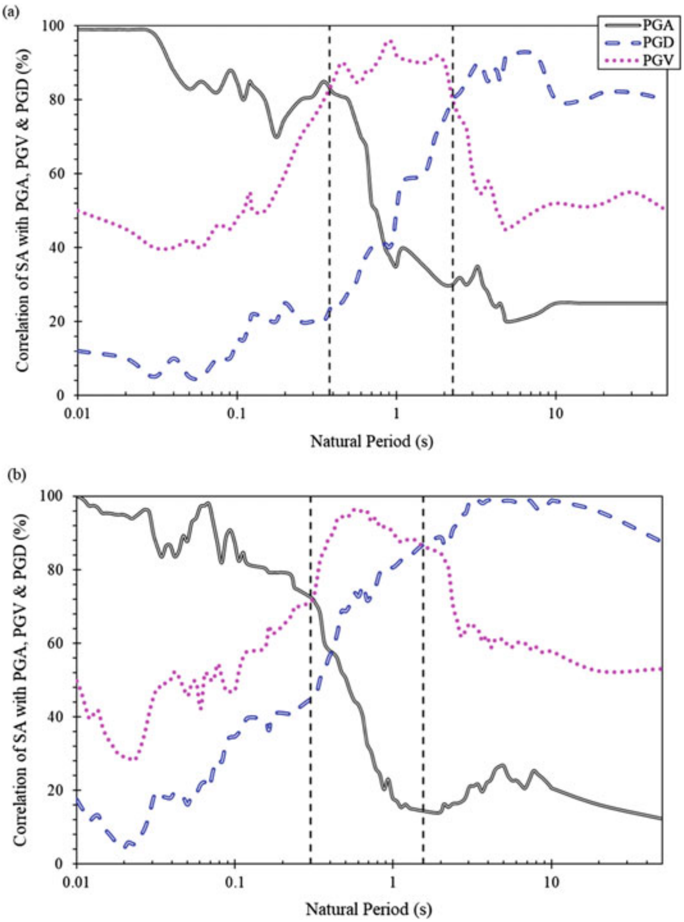

Fig. 1.8 Correlation of SA at various periods with PGA, PGV, and PGD for **a** Indo Gangetic Basin and **b** Stable continental region for bedrock

seismology and earthquake geotechnical problems through research and respective publications found at http://civil.iisc.ernet.in/~anbazhagan/List%20of%20Publications.html. Here, acceleration data complied from a different source and presented in the previous publications for rock sites are used for developing a 5% damped design spectrum for the horizontal and vertical components of ground motions. Since seismicity, seismotectonic, and subsurface information of North India (Himalayan region) are completely different from South India, a separate approach has been made to develop a design spectrum using the same methodology but corresponding data. Rock site acceleration time histories from NI and SI are used separately to develop the design spectra. Since the available rock sites' data are very little for south India (intraplate region), data from other intraplate areas of the world are added to the south Indian dataset.

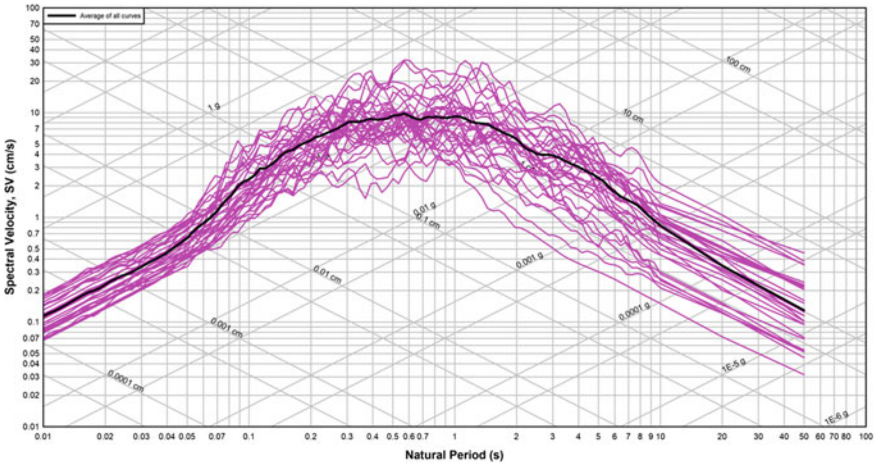

Fig. 1.9 Tripartite plot of horizontal seismic ground motions recorded at bedrock sites in North India

The tripartite plot of horizontal ground motions was recorded at bedrock sites at NI, as shown in Fig. 1.9. The procedure to calculate smoothed and normalized design spectrum from acceleration ground motion record is explained in the previous section. The median normalized spectrum versus normalized spectral period is arrived for NI and is shown in Fig. 1.10a. The shaded area in Fig. 1.10a corresponding to ±1 standard deviation about the median. The smooth response spectrum has been obtained afterwards by using the least-squares fitting of straight-line segments through the median curve shown in Fig. 1.10b. Figures 1.10b show the smooth medium spectrum of north India covering the Himalaya, northeast and northwest, and Indo-Gangetic Basin. The factors above unit PGA, PGV, and PGD, i.e., α_A, α_V, and α_D for the Himalayan region are 2.29, 1.97, and 2.05, respectively. The control periods for acceleration, velocity, and displacement section of the spectrum, i.e., T_2, T_3, and T_4 found to be 0.15, 0.38, and 2.33 s, respectively.

The tripartite plot of horizontal ground motions of bedrock sites from the stable continental region of the world i.e., SI is shown in Fig. 1.11. A similar procedure discussed above has been used to arrive median normalized spectrum versus normalized spectral period is given in Fig. 1.12a, for stable continental data. The shaded area in Fig. 1.12a corresponds to ± 1 standard deviation about the median. Figure 1.12b shows the smooth response spectrum obtained by using the least-squares fitting of straight-line segments through the median curve. The factors of α_A, α_V, and α_D for the stable continental region is 2.18, 2.04, and 1.55, respectively. Here, we can notice that there is a slight difference that can be observed for both the region factors at rock sites. The control periods of T_2, T_3, and T_4 found to be 0.08, 0.28, and 1.52 s for SI, which is considerably different from NI. These observations are for 5% damping design spectrum factors using available data, and adding more regional data may refine findings.

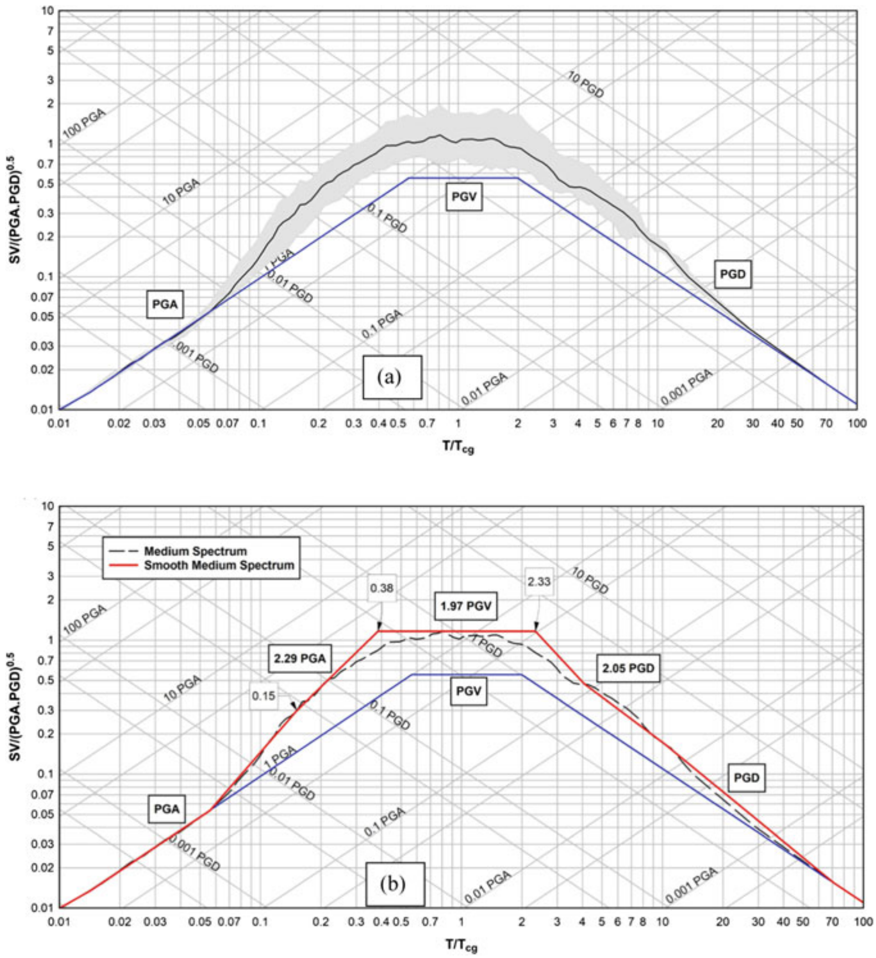

Fig. 1.10 North Indian normalized 5% damping median spectrum of horizontal seismic ground motions recorded at bedrock site (**a**) and smooth medium spectrum (**b**)

1.8 Code Design Spectrum

Many seismic codes have included the significant influence of the local site effect in their recent provisions. After the 1994 Northridge earthquake, seismic codes such as the National Earthquake Hazard Reduction Program [49], the Uniform Building Code [31], the International Building Code [50], and Eurocode 8 (EC8) [51] accounted for the site effects using the elastic design response spectra. In most modern seismic designs, the estimation of a seismic force on a typical structure is based on the 5% damped design response spectrum of recorded data in the region. In India, limited attempts have been made to develop the design spectrum with different damping

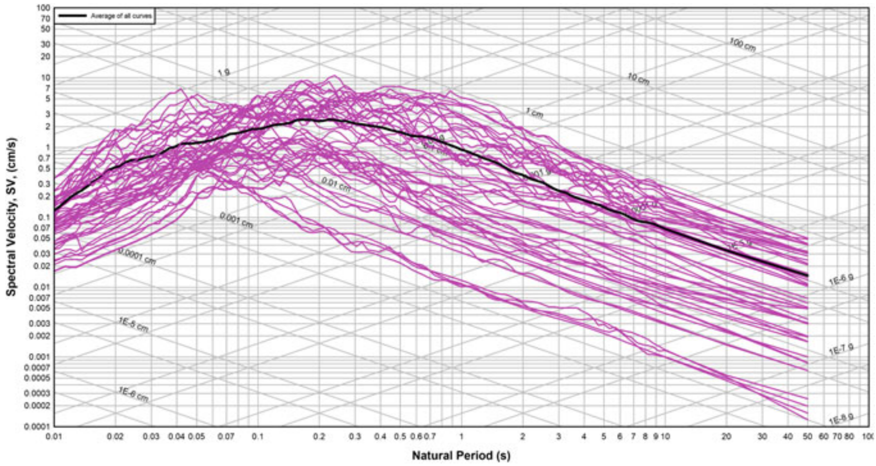

Fig. 1.11 Tripartite plot of horizontal seismic ground motions recorded at bedrock sites in the stable continental region, i.e., South India

level considering regional recorded data; however, some attempt has been made by Anbazhagan et al. [23]. Generally, the design spectra of a given site are obtained by modifying the uniform hazard spectrum by considering site factors corresponding to a particular seismic area. Conventionally, the design force is specified via response spectrum amplitude. However, with the increase in complexity of modern structures, to understand the seismic performance of the structure, it is now essential to define the amplitude and shape of the design spectra. EC8 [51] defined the normalized elastic design response spectra based on effective ground acceleration at the rock site, and the shape has been defined using the three corner periods. Similarly, the BIS, IS:1893 [11] defined the normalized elastic response spectra based on the effective ground acceleration at rock sites; whereas the recent international seismic codes (i.e., NEHRP, BSSC [52]) refined the elastic response spectra using the two parameters, namely spectral acceleration at short period and at a period of 1 s. The soil amplification has been accounted for using site amplification factors.

The work regarding the development of building codes began in Italy in 1908, after the Messina disaster; in Japan following the 1923 Tokyo earthquake; in California after the 1925 Santa Barbara earthquake [53], and in India after the 1934 Bihar–Nepal earthquake. Most of the building codes around the world have adopted the Newmark–Hall spectrum with some modifications [45]. New elastic design response spectra for corresponding rock sites with 5% damping ratio can be proposed in two ways. One is similar to EC8 [51], i.e., normalized elastic design response spectra which is based on one parameter (effective ground acceleration at rock). The other one, i.e., elastic design response spectra based on two input parameters that are spectral acceleration at a short period and at a period of 1 s, which is similar to NEHRP.

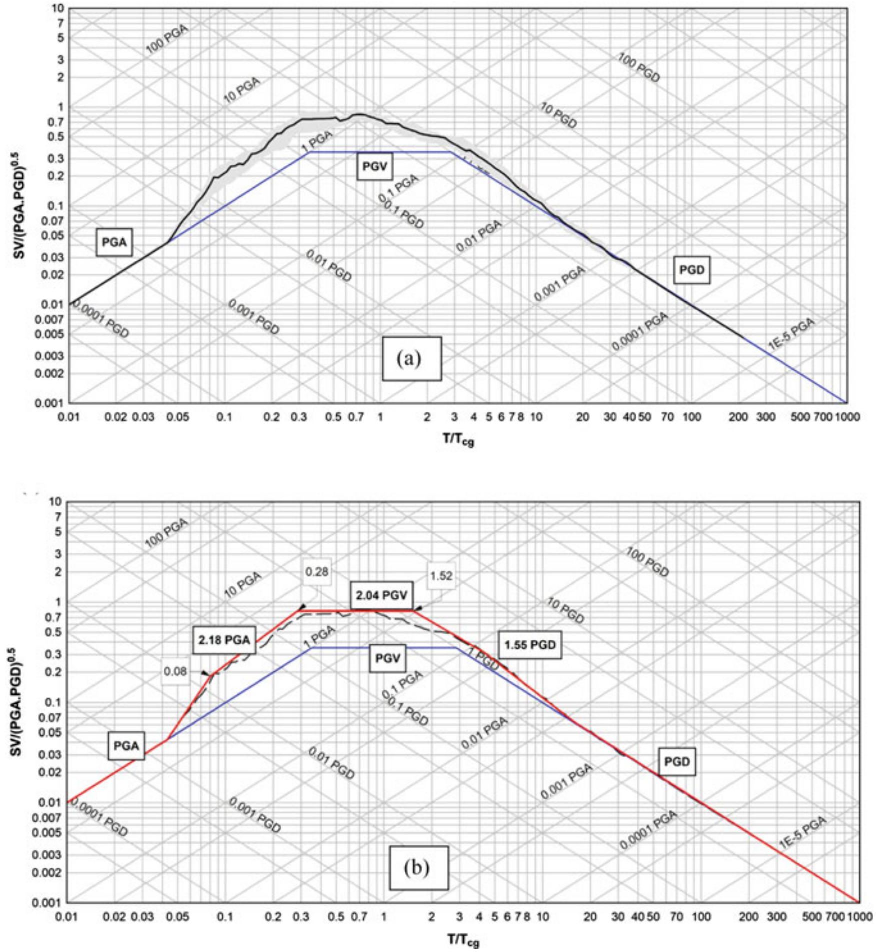

Fig. 1.12 South Indian normalized 5% damping median spectrum of horizontal seismic ground motions recorded at bedrock sites (**a**) and smooth medium spectrum (**b**)

1.8.1 Elastic Design Response Spectra for Single Input

The current Eurocode 8 (EC8, CEN 2005) [54] defined the two standard shapes for the linear response spectrum, viz. Type 1 and Type 2. Type 1 corresponds to more energy, and Type 2 corresponds to less energy in the long period motions. The former is used for the high seismicity area and the latter for the low seismicity area. The factors that determine the shape of the spectra depend on the ground acceleration at rock conditions and soil amplification factor, i.e., S, which accounts for the local soil and site effect. Further, the corner periods are defined as T_B, T_C, and T_D. The peak of the spectral amplitude is defined as 2.5 ηS, where η is the damping ratio, i.e., 5%. The typical plot for EC8 is shown in Fig. 1.13a. In the sixth revision of BIS:1893 [11], two methods, viz. equivalent static method and response spectra methods, are proposed to construct the acceleration design spectra for the different zone. However, unlike EC8, the SA coefficients are capped at 2.5 by classifying soil into three categories based on SPT-N value.

EC8 has proposed the generalized equation for constructing the normalized elastic response spectrum. The same equations are used in the present study to derive the elastic response spectra for the NI and SI. The general form of equations for the elastic response spectra for 5% damping is as

$$0 \leq T \leq T_B : \frac{S_a(T)}{PGA_{\text{rock}}} = s.\left[1 + \frac{T}{T_B}.(\beta - 1)\right] \tag{1.6}$$

$$T_B \leq T \leq T_C : \frac{S_a(T)}{PGA_{\text{rock}}} = s.\beta \tag{1.7}$$

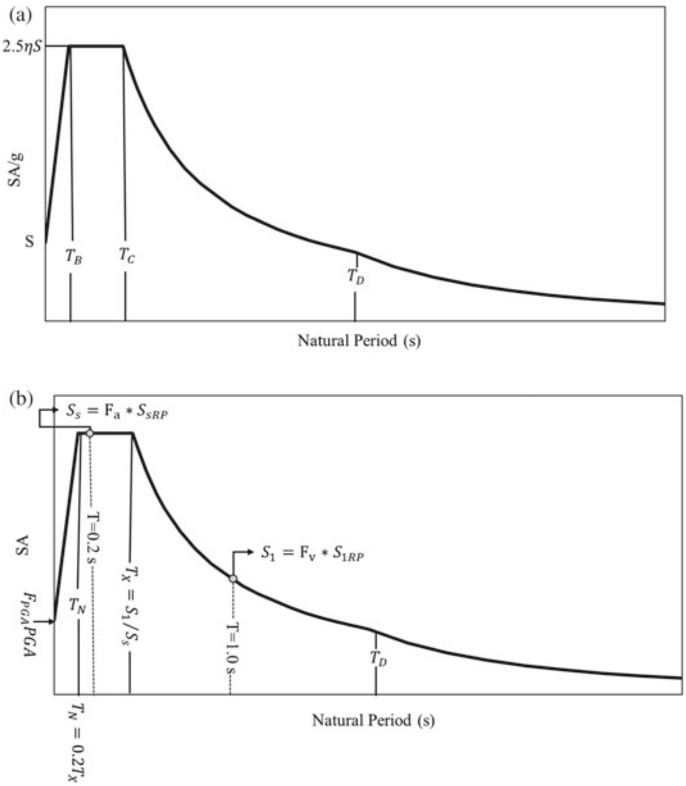

Fig. 1.13 Typical seismic design response spectrum proposed by EUROCODE (EC8). Typical seismic design response spectrum proposed by NEHRP/ASCE [55]/AASHTO [56]

$$T_C \le T \le T_D\colon \frac{S_a(T)}{PGA_{\text{rock}}} = s.\beta\frac{T_C}{T} \tag{1.8}$$

$$T_D \le T\colon \frac{S_a(T)}{PGA_{\text{rock}}} = s.\beta.T_C\frac{T_D}{T^2} \tag{1.9}$$

Here, PGA_{rock} is the design ground acceleration at rock-site conditions, S and β are the soil amplification and spectral amplification factors. T_B and T_C are the limits of constant acceleration branch and T_D is the beginning of the constant displacement range of the spectrum.

1.8.2 Elastic Design Response Spectra for Two Inputs

In 1997, the Uniform Building code [31] used C_a to construct the acceleration region and C_v to construct the velocity region. The 1997 NEHRP [49] site coefficients for a short period i.e., F_a and long period i.e., F_v were defined during the 1992 national workshop. F_a and F_v are defined as spectral acceleration ratios averaged over period ranges of 0.1–0.5 s and 0.4–2.0 s respectively; whereas the site factors at a short period or 0.2 s (F_a) and long period or 1.0 s (F_v) are recommended by the American Society of Civil Engineers Standard ASCE 7-10 [55], the International Building Code [50], and the AASHTO guide [56] that was first defined in the 1994 NEHRP provisions [49]. F_a defined in the IBC is the average value and F_v is approximately the average $+1\sigma$ amplification values [57]. In IBC, F_a is estimated for the short-period band 0.1–0.5 s, whereas, F_v is defined over the long-period band 0.4–2.0 s [57]. These F_a and F_v values are used for constructing the acceleration response spectra for different seismic site classes based on NEHRP. The design response spectra are constructed from 5% damping at 0.2 s (S_S) and at 1 s (S_1) that are calculated from probabilistic seismic hazard analysis. The control period that defines the transition between the acceleration and velocity-sensitive regions is computed as $T_X = S_1/S_s$ and the period at the beginning of the flat acceleration-sensitive region is defined as $T_N = 0.2T_X$. A typical design response spectrum is given in Fig. 1.13b.

T_N, T_X, and T_Y are the control periods. T_N and T_X are the limits of constant acceleration branch and T_Y is the beginning of the constant displacement range of the spectrum.

$$T_X = S_1 T_1/S_s \tag{1.10}$$

$$T_N = T_X/\kappa \tag{1.11}$$

These control periods in this case depend on S_s and S_1. T_Y is analogous to T_4 (see Fig. 1.6) and equal to T_D and the values can be determined from Table 1.3 ($T_Y = T_D$). It can be noted that constant periods T_N and T_X are analogues to T_2 and T_3 in Fig. 1.6

Table 1.3 Parameters of the proposed new design response spectrum at rock site for 5% damping using Indian earthquake data

Parameters	North India (interplate)	South India (Intraplate)
T_B	0.15	0.08
T_C	0.38	0.28
T_D/T_Y	2.33	1.52
S	1.00	1.00
β	2.29	2.18

[45]. κ which is the ratio of the T_X/T_N is defined based on T_2 and T_3 for rock sites of NI & SI. κ value of 2.5 is derived by Malhotra [45] based on 63 rock sites recorded seismic ground motion and 4 as determined by NEHRP, ASCE and AASTHO. We believe that κ value for rock sites of NI and SI can be different. This may be because the design spectrum is conservative and it is a composite of several seismic events.

Further, S_s and S_1 are defined as

$$S_s = \mathrm{F_a} * S_{sRP} \tag{1.12}$$

$$S_1 = \mathrm{F}_v * S_{1RP} \tag{1.13}$$

Here, S_{sRP} and S_{1RP} are the reference maximum spectral acceleration corresponding to the constant acceleration branch and at a period of 1 s of the horizontal 5% damped elastic response spectra on bedrock. This method required input of PGA, average spectral factors [F_a and F_v] and spectral acceleration at constant acceleration region and 1 s [S_{sRP} and S_{1RP}]. As the author believes, that is no systematic futuristic hazard analysis was developed for NI and SI and providing this spectrum may lead to error, hence not exclusively included here. In this study, we developed a design spectrum by the first approach i.e., similar to Eurocode, which is also the current Indian code of practice. Then developed spectra are further compared with the Indian seismic code spectra at different revisions.

1.9 New Design Spectrum

1.9.1 Horizontal Motion Design Spectrum

The parameters S, β, T_B, T_C, and T_D depend on site/soil class and seismicity, as explained above. These periods are determined as per the [45] procedure in this study for both region separately. T_B, T_C, and T_D are analogues to T_2, T_3, and T_4 in Fig. 1.6 and the parameters β, T_B, T_C, and T_D have been determined using the normalized spectrum shown in Figs. 1.10b for NI and 1.12b for SI. S is unity for rock site (in this study) and more than unity for other soil sites depending on the local site effects. In the present study, these parameters are derived based on the

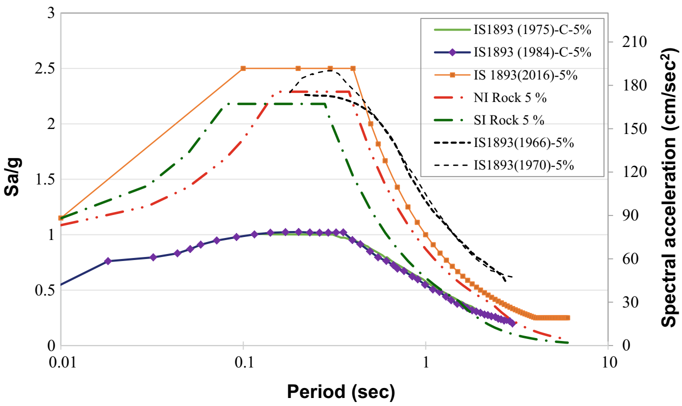

Fig. 1.14 Newly developed horizontal spectrum using Indian data and 5% acceleration, velocity, and displacement spectrum at rock sites for North India (NI) and South (SI) and also comparison with different versions of IS 1893 spectrum. IS 1893 [6, 7] spectrum with secondary Y-axis

interplate (North) and intraplate (South) region of India. Considering the spectra in the two regions separately helps better representation of the shape of the response spectra. β, T_B, T_C, and T_D are determined based on the shape of the normalized response spectra at rock site conditions. These factors are the result of fitting the smooth spectrum to the median normalized spectrum. The values are given in Table 1.3. Figure 1.14 shows elastic design response spectra for single input similar to EC8 for NI and SI. We can notice that data based newly derived spectrum is lower than most of IS 1893 spectra. Further cut-off period for acceleration, velocity and displacement and respective amplitudes are lower than the current codal provision of IS1893 (2016). This spectrum is valid only for 5% damping and other damping reader can refer [23] or our future work. We are also working on the development of two input based spectrum similar to NEHRP and ASCE with bedrock level seismic hazard maps showing PGA, S_s, S_1 and respective factors.

1.9.2 Vertical Motion Design Spectrum

Generally, all code design spectrum developed are based on horizontal spectrum and have considered some reduction factor for vertical motions without studying the data. Indian code, IS 1893, suggested that the vertical seismic coefficient, where applicable, should be taken as half of the horizontal seismic coefficient given in 1962, 1966, 1970, 1975 and 1984 version values [in Fig. 1.4]. In 2002 and 2016, versions of IS 1893 recommended that the design acceleration spectrum for vertical motions may be taken as two-thirds of the design horizontal acceleration spectrum. Generally, it is assumed that the vertical spectrum is 2/3 of the horizontal spectrum is a recent code recommendation. This indicates that frequency distribution in horizontal spectra is the same as vertical spectra for any region. However, many studies [45] have proved that the frequency distribution of both spectra is different. This has been observed in various Indian subcontinent earthquakes (e.g., 2015 Nepal Earthquake, 2001 Bhuj Earthquake etc.). Hence, an attempt is made to determine the difference in the horizontal and vertical spectrum for the Indian data. Similar to [45], the vertical to horizontal ratio is calculated for 50 rock ground motions for North India data. The vertical to horizontal ground motion ratio is calculated for the different periods. The median vertical to horizontal ratio is derived for both rock sites. Figure 1.15a shows the vertical spectrum derived from the actual data along with the horizontal spectrum from data and 2/3 horizontal spectrum as a vertical spectrum. We can see a considerable difference between vertical horizontal and follow 2/3 based western countries recommendation is also not appropriate for North India. In comparison, it can be observed that control periods and amplification are considerably different for the horizontal spectrum. Further proposed vertical design response spectra are compared with the rock site of IS 1893 [11] horizontal and vertical spectrum and shown in Fig. 1.15b. Figure 1.15b shows that the actual North India earthquake data-based vertical spectrum is considerably different from the IS 1893 recommended American earthquake based spectrum for the horizontal and vertical components. This study developed the first time smoothed and normalised design spectrum considering acceleration, velocity, and displacement response of Indian earthquakes. These spectra can be further reviewed and modified by adding more and more data from rock sites in respective regions.

1.10 Summary and Conclusion

Several researchers summarised and reviewed Indian seismicity, seismotectonic, hazard analysis, and IS 1893 code in the literature. But most of them highlighted issues, but a minimal attempt was made to provide solutions based on the state-of-the-art knowledge and also using regional recorded earthquake data. Even though considerable effort has been made to record digital data of local earthquakes since 1997 and digitalization of analogue records of old significant earthquakes, very limited data is available to engineers. IISc complied earthquake data from different sources with a non-sharing agreement and used it to arrive at more realistic regional seismotectonic parameters, source parameters, and ground motion simulation and models. These models and methods are highly useful to arrive a reliable futuristic seismic zonation map of India. This paper summarized the diversity of Indian seismicity, seismotectonic and subsurface layers. It then highlighted the importance of a region-specific approach for arriving seismic hazard values at bedrock level based on region-specific rupture-based seismic hazard approach developed at IISc. A study of IS 1893 [5–11] codes indicates that the design spectrum of the given code was adopted from American data and not valid for Indian conditions due to diversity in seismicity and soil type. Collected time history data at the bedrock level has been used to arrive at smoothed and normalized design spectrum parameters for north (interplate) and

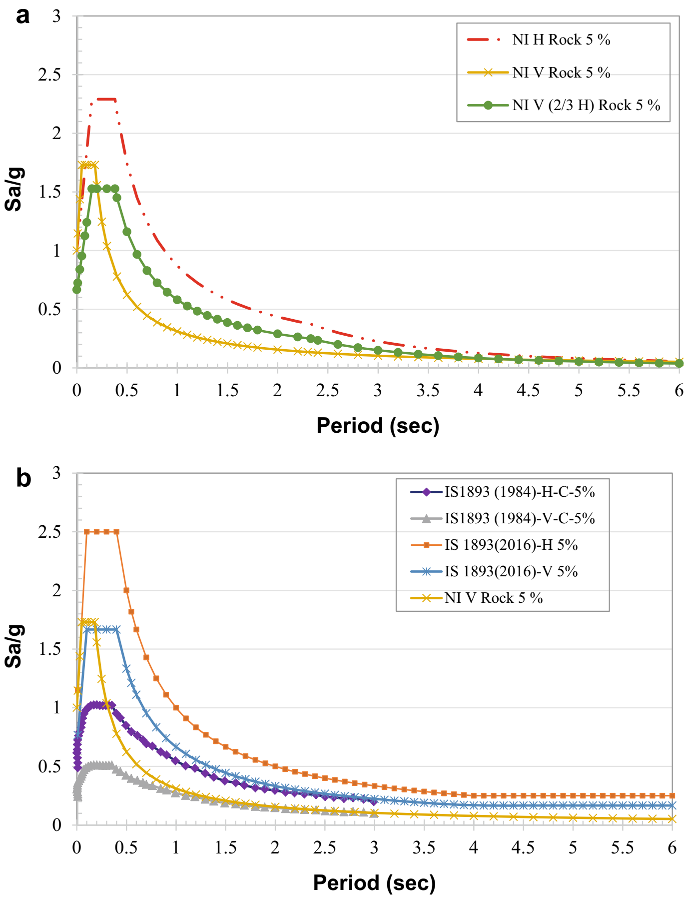

Fig. 1.15 Comparison of **a** proposed vertical (PV) design response spectrum with horizontal design spectrum and 2/3 factor of horizontal spectrum values for bedrock condition with 5% damping for in NI. **b** Proposed vertical design response spectrum (V) compared with horizontal (H) and vertical (V) suggested in IS:1893 [11] and (1985)

south (intraplate) India separately for the first time. We found that spectral amplification factors above unit PGA, PGV, and PGD and cut-off time for acceleration, velocity and displacement-sensitive section of the spectrum are different from the spectrum given in IS 1893. These parameters were also different from South and North India due to variations in seismotectonic characters. Based on regional data analysis first-time design spectrum for bedrock sites with 5% damping was developed and presented in the paper. Normalized elastic design response spectra based on one parameter (effective ground acceleration at rock). For that S, β, T_B, T_C, and T_D have been derived for the proposed seismic site classification to derive the normalized design response spectrum. T_B and T_C which define the constant spectral acceleration region are derived as 0.15 and 0.38 s in the case of bedrock in NI and 0.08 and 0.28 s in the case of bedrock in SI. Similarly, β has been increased by 1.05 times in the case of NI when compared to SI at the bedrock site. It has been observed that the value of the control period and spectral amplification factors derived in the present study based on region-specific seismic data is different from the other region seismic codes. This study can be further refined by adding more data and also for different damping levels. The availability of more and more recorded earthquake data and systematic site response analysis can help to drive the design spectrum for various soil sites in the future.

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