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Earthquake Engineering and Disaster Mitigation

Contributions in the Honour of Late Professor D. K. Paul

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Preface I

Professor D. K. Paul obtained his B.Sc. Engineering from the University of Lucknow (1965), B.E. in Civil Engineering (1969), and M.E. in Earthquake Engineering (1971) from the erstwhile University of Roorkee. After completing his masters, he joined as a faculty member in the Department of Earthquake Engineering, University of Roorkee in 1972. In 1978, he went on to do his Ph.D. from the University of Wales, Swansea, UK, under a Commonwealth Scholarship and received it in 1982. He continued there as a postdoctoral researcher until 1986 before returning to the University of Roorkee. He served the University of Roorkee in many capacities such as Professor and Head, Department of Earthquake Engineering, Dean of Faculty Affairs, and Deputy Director. He was also the founding Head of the Centre of Excellence in Disaster Mitigation & Management and has actively participated in the various activities of the center. Professor Paul's contribution in postgraduate teaching in Earthquake Engineering and National Capacity Building Programs in Earthquake Engineering Education has helped greatly in Earthquake Disaster Reduction. As a part of the awareness program, he disseminated the basic knowledge on Earthquake Engineering and Earthquake Disaster Mitigation to the masses through simple lectures, guidelines, manuals, booklets, TV films, Symposia/Conferences, etc. These have made an immense impact on the Disaster Mitigation efforts in the country. After serving for 40 years, he retired as Professor/Deputy Director, IIT Roorkee. He continued to serve IIT Roorkee as an Emeritus Fellow.

Professor Paul was a leading authority in the field of Earthquake Engineering and Earthquake Disaster Mitigation. He was consulted for the assessment of the Seismic Safety of many Special Structures in the country requiring Earthquake Resistant Analysis and Design. He has made significant contributions in Earthquake Resistant Analysis and Design of Special Structures such as concrete gravity dams, earth and rockfill dams, bridges, nuclear power plants, multi-story buildings, etc., resulting in Earthquake Disaster Reduction in the country. He has served as Chairman and Member of several National Task Forces, Investigative Teams, National Expert Committees on Disaster Mitigation issues constituted by the DST, Ministry of Home Affairs, National Disaster Management Authority, Government of India, etc. He has also received several research awards and is a Fellow of several National Technical

Societies. Professor Paul served as the Chairman of the Earthquake Engineering Sectional Committee, CED 39 of the Bureau of Indian Standards. He was a Fellow of the Indian National Academy of Engineers (FNAE); the Indian Institute of Engineers (FIE); and the Indian Society of Earthquake Technology (FISET). He also served as the Vice President (1995–1997 & 1997–1999) and President (2007–2009 & 2009–2011) of the Indian Society of Earthquake Technology (ISET).

Professor Paul was the Chairman and Member of various national committees constituted by various ministries of the Government of India. He was Chairman of the Working Committee of Experts for Vulnerability Analysis and Risk Assessment constituted by NDMA, the National Steering Committee (NSC) on Seismic Microzonation of major cities constituted by the Ministry of Earth Sciences (MoES), the Working Group on Seismic Microzonation of Delhi Region constituted by the Department of Science and Technology (DST), and the Expert Group for the Preparation of a Comprehensive Proposal on Microzonation of Guwahati, constituted by the Ministry of Science and Technology (MoST). Also, he was a Member of the Expert Committee on 'Retrofitting of District Hospitals under National Earthquake Risk Mitigation Project (NERMP)' set up by the NDMA and the Environment Assessment Committee (MEAC) on River Valley Projects set up by the Ministry of Environment & Forest (MoE&F). The Ministry of Home Affairs (MHA) has appointed him Programme Coordinator of the National Programme for Capacity Building of Engineers in Earthquake Risk Management (NPCBEERM), Convener of the Committee on Model Building Byelaws and Review of City, Town and Country Planning Act and the Zoning Regulations, and Member of the National Core Group for Earthquake Disaster Mitigation. In view of the humongous contributions made by Professor Paul, the Indian Society of Earthquake Technology (ISET) had planned to bring out a Special Commemorative book volume entitled, "Earthquake Engineering and Disaster Mitigation—Contributions in the honour of Late Professor D. K. Paul".

Roorkee, India — Ravi S. Jakka
Roorkee, India — Yogendra Singh
Guwahati, India — T. G. Sitharam
Roorkee, India — Bal Krishna Maheshwari

Preface II

The editors are pleased to present this text to the readers on Earthquake Engineering and Disaster Mitigation—Contributions in the honour of Late Professor D. K. Paul. Extensive research study has been performed on the aspects of earthquake engineering and allied areas across the world, quite naturally because of its significance as well as relevance to the life safety of people. In the present edited book volume, the authors of various chapters have delineated a vast spectrum of research works carried out under several disciplines and sub-disciplines of earthquake engineering and technology. Brief coverage of various chapters is presented below.

Anbazhagan et al. (2023) presented seismic design criteria in the Indian Seismic Code IS1893 since its development, state-of-the-art procedure for the seismic hazard estimation, and the development of seismic design spectrum at Indian Rock Site from North India and South India seismic data separately. In this study, 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. This study has forecasted the fact that North and South Indian spectrums are different from the IS-1893 spectrum as the signature of each seismotectonic region is reflected in the proposed new spectral shape.

Narayan et al. (2023) presented relationships for predicting the amplification of SH-wave across two-dimensional deep basins at a fundamental frequency. In this study, numerical simulations and computation of spectral amplifications of the SH-wave across the considered rectangular and elliptical basins for different shape ratios, impedance contrast, sediment damping and development of relations to predict the amplification of SH-wave at fundamental frequency across 2D deep basins across the deep rectangular and elliptical basins have been presented. This study has developed relations for predicting the amplification at fundamental frequency across rectangular and elliptical deep basins in terms of amplification at center of respective basin, at an offset from the basin center as well as at half width of the basin. A comparison of numerically computed amplification at fundamental frequency across rectangular and elliptical deep basins with those obtained using developed relations reveals that the percentage differences are within the permissible limit.

Nath et al. (2023) performed earthquake-induced landslide hazard evaluation for seismic microzonation with emphasis to Garhwal Himalayas study area. Consideration of probabilistically generated peak ground acceleration for 10% exceedance probability in 50 years as a landslide triggering factor has been adopted in this study. This study recognized 464 landslides and 8 preparatory causative factors. The study depicted that around 40% of the study area falls under the zones of high and very high seismically induced landslide hazards.

The aspects of inherent randomness in the underlying geotechnical and geological formations make its characterization highly site-specific. Shreyasvi and Venkataramana (2023) outline the scope of a non-ergodic PSHA in the Indian scenario and the existing practices in capturing the uncertainties introduced by the site component. The authors believe that this manuscript can provide insight into improving the existing site-specific PSHA practices in the country.

Rangaswamy et al. (2023) presented a study on characterizing the dynamic properties of the ground soil profiles existing in southern Calicut city nearby the National Institute of Technology Calicut region. In this study, field MASW tests were carried out at 48 representative sites by using a geode seismograph. This study depicted that the average shear wave velocity (V_{s30}) of the uppermost 30m depth of soil strata is within the range of 273 to 615 m/s.

Kumar et al. (2023) in their study reported a comparative influence of two different types of loading mechanisms on the frequency-dependent dynamic properties of the cohesionless Brahmaputra sandy soil. In this study, both stress-controlled as well as strain-controlled experiments were performed on the aforementioned geomaterial which depicted that the loading frequency is found to influence the shear modulus and damping ratio with a contradicting response between the parameters. Further, this study also states that during strain-controlled loading, the frequency of loading is found to influence significantly the damping ratio only, whereas, for stress-controlled loading, both the damping ratio and shear modulus are found to be affected significantly by the loading frequency.

Padmanabhan and Maheshwari (2023) investigated the reliquefaction behavior of the Solani sand specimen by varying the acceleration amplitude and shaking duration subjected to repeated shaking events with two different shaking patterns. Experimental studies were performed with the saturated sand specimen at 25% relative density in a tank with repeated sinusoidal shaking. The experimental results demonstrated that the preshaking effect and shaking pattern are critical in influencing the reliquefaction potential of sand deposits and the pore pressure analysis depicts that the tendency of liquefaction increases even at lower acceleration with higher shaking duration.

Bharathi et al. (2023) investigated the behavior of batter piles under the influence of machine-induced vibrations. In this study, a series of dynamic lateral and vertical loading tests were conducted on a vertical piles and batter piles embedded into a layered silty sandy soil. Accelerometers were deployed on the pile cap in order to obtain the dynamic response of these piles. The results show that the resonant frequency of the soil–pile system decreases by 37–50% along the lateral direction and 43–50% along the vertical direction, with increasing force level. This study also depicted that in both lateral directions, the rotational stiffness of the soil–pile system decreases nonlinearly, whereas the damping ratio increases nonlinearly with an increase in lateral strain.

The catastrophic failure of pile foundations used for the support of bridges and other structures in liquefiable soils is still observed after every major earthquake. Basavanagowda et al. (2023) conducted three-dimensional finite difference analyses in order to evaluate the influence of non-liquefiable crust overlaid by a liquefiable crust with the pile embedded into non-liquefiable soil layer below the liquefiable soil in both level and sloping ground. Analysis was carried out for different cases of pile tip embedment into the liquefiable and non-liquefiable soil subjected to the 2001 Bhuj Earthquake motion. This study depicted that the maximum bending moments occurred at the interface of liquefiable and non-liquefiable layers.

Kumar and Takahashi (2023) investigated the efficacy of a hybrid foundation in order to mitigate liquefaction-induced effects under strong sequential ground motions. As per this study, the hybrid foundation is a combination of the gravel drainage system and friction piles having spiral blades devised under the footing as a hybrid mitigation technique against the liquefaction-induced effects on a shallow foundation. A series of dynamic centrifuge experiments were carried out to investigate the effectiveness of a hybrid foundation in the liquefiable ground under strong sequential ground motions. This study depicted that the second sequential ground motion is found to be diminishing the mitigation efficacy of the proposed hybrid foundation in comparison with the first sequential ground motion and the implications of strong sequential ground motions have also been elaborately presented.

Srivastav and Satyam (2023) investigated the contribution of vertical seismic coefficient in seismic analysis of hydro-tunnel in rock. This study provides a numerical analysis of the seismic response of a circular lined tunnel running through a jointed rock mass. The effect of tunnel depth, frequency, and Peak ground acceleration on axial force produced in the tunnel liner is also assessed in this study. This study concludes that incorporating the vertical seismic coefficient in the formulation results in a much higher maximum axial force during seismic loading and negating the vertical seismic coefficient might result in an underestimation of the earthquake effect.

Subramanya et al. (2023) conducted experimental studies to assess the dynamic response of a ten-story scaled building model supported on pile and piled raft foundations in soft clay. In this study, the response of the model structure was investigated for fixed and flexible base conditions considering two types of foundation systems, namely supported by pile groups and small piled raft foundations embedded in soft clay. This study delineated the fact that soil–pile structure system amplifies the lateral deflections and the story drift of the superstructure in comparison with the fixed base.

Sharma et al. (2023) investigated the seismic performance of masonry-infilled reinforced concrete frame building designed as per Indian codes. The current Indian design codes do not adequately cover the design of frame buildings with masonry infills. As a result, the designers continue to design frame buildings while ignoring the infills. This article reviews provisions of different national codes regarding the design of masonry infilled frames. Further, the effectiveness of the current design procedure being followed in the Indian design industry is also evaluated. Performance-based seismic engineering framework has been utilized in this study for quantifying the performance of frame designed using the mentioned design procedure.

It is indeed pleasing to see that a wide variety of topics have been dealt with in these chapters of the book. We feel that these contributed chapters in this book have elaboratively highlighted tenets of Earthquake Engineering and Disaster Mitigation aptly. Therefore, we believe that the latest developments in earthquake engineering and allied disciplines presented through these 13 chapters will prove to be highly informative to the readers and pave ways for further research. We thank all the staff of Springer for their full support and cooperation at all the stages of the publication of this book. We thank and acknowledge the service of authors and reviewers for their valuable time and efforts. We do hope that this book will be beneficial to students, researchers, and professionals working in the field of geotechnical earthquake engineering. The comments and suggestions from the readers and users of this book are most welcome.

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Dr. Yogendra Singh is Railway Bridge Chair Professor, and former Head, Department of Earthquake Engineering, at Indian Institute of Technology Roorkee. He obtained his B.E. in Civil Engineering from IIT Roorkee (then University of Roorkee) in 1989 in First Division with Honours and M. Tech. and Ph.D. in Structural Engineering from IIT Delhi in 1990 and 1994, respectively. His has worked extensively on Performance Based Design of Buildings and Bridges; Seismic Vulnerability and Risk Evaluation; Non-Linear Modelling and Analysis; Seismic Evaluation and Retrofitting of Structures; and Earthquake Engineering in Hilly Regions. He has supervised 17 Ph.Ds., published more than 85 research articles in refereed journals and presented more than 100 papers in national and international conferences. He has been member of several expert teams for post-earthquake damage surveys and is convener of the BIS expert group on Performance Based Seismic Design of Structures. He is Fellow of Indian Society for Earthquake Technology, Life Member of Institution of Engineers (India), Member of American Society of Civil Engineers, and Earthquake Engineering Research Institute. He is recipient of IIT Roorkee Outstanding Teacher Award—2006, 2022, AICTE Career Award, Dr. Jai Krishna Prize and Medal, and Sir Arthur Cotton Memorial Prize.

Dr. T. G. Sitharam is the Director of Indian Institute of Technology Guwahati, Assam since July 2019. He is a member of the Science and Engineering Research Board (SERB), Established through an Act of Parliament: SERB Act 2008, Department of Science & Technology, Government of India. He is a Senior Professor in the Department of Civil Engineering, Indian Institute of Science (IISc), Bangalore, and served IISc for more than 27 years. He was Chairman of the Board of Governors at IIT Guwahati during 2019–2020. He was the former Chairman, Research Council, CSIR- CBRI (Central Building Research Institute, Roorkee). He is holding the position of Director (additional charge) of Central Institute of Technology, Kokrajhar, Assam (A Deemed to be University), since May 2021. Over the last 35 years, he has carried out research and development in the area of geotechnical and infrastructure engineering, seismic microzonation and soil dynamics, Geotechnical earthquake engineering and has developed innovative technologies in the area of earth sciences, leading to about 500 technical papers, 20 books with Google scholar H-index of 47 and I-10 index 137 with more than 7175 citations. He has guided 40 Ph.D. students and 35 Master's Students. He was listed in the world's top 2% of scientists for the most-cited research scientists in various disciplines by Stanford University in 2020. His name appeared again in the top 2% of scientists IN Elsevier by Stanford University in 2021. His broad area of research falls into Geotechnical Infrastructure engineering, earth sciences, hydrology, seismology, and natural hazards. He has carried out Seismic microzonation of many urban centers in India and he is an authority on seismic microzonation and site effects. Presently, he is the President of the Indian Society of Earthquake Technology and he was the chairman of the 7th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics held in July 2021. He is the chief editor of the International Journal of Geotechnical Earthquake Engineering, (IJGEE), PA, USA since 2010. He is the Editor-in-chief, Springer Transactions in Civil and Environmental Engg. series, Book Series, Singapore. He is the Fellow of ASCE, Fellow of ICE (UK), Diplomat of Geotechnical Engineering (D.Ge.) from Academy of Geo-Professionals, ASCE; Fellow of IGS, ISET, ISES, and many other Societies. Presently, he is Executive Council member of AICTE and Chairman, Eastern Zonal committee of AICTE. He is Chairman (Designate) of All India Council for Technical Education, Govt. of India. He is also a certified professional engineer and a chartered engineer from the Institution of Engineers.

Dr. Bal Krishna Maheshwari recently served as a Shamsher Prakash Chair Professor at Department of Earthquake Engineering, IIT Roorkee. He secured Ph.D. from Saitama University Japan, worked for about two years in industry in Tokyo, Japan and then joined Washington University in St. Louis, Missouri, USA as a post-doctoral fellow. Since Dec. 2004, Dr. Maheshwari is a faculty at Department of Earthquake Eng., IIT Roorkee, India. Professor Maheshwari is working in the areas of Dynamic Soil-Structure Interaction, Liquefaction, Dynamic Soil Properties, Constitutive Modeling, Nonlinear Finite Element Analysis, Slope Stability, Landslides, Seismic Analysis of Tunnels and Disaster Mitigation & Management. He served as an Associate Editor of International Journal of Geomechanics, ASCE and as an Editor of ISET Journal of Earthquake Technology. Professor Maheshwari is a member of ASCE, EERI, ISSMGE, IACMAG, a life fellow of ISET, IGS, IEI and IWRS. He has been awarded "Excellent Research Contribution Award" in Kyoto, Japan in year 2014 and "John Booker Medal" in Torino, Italy in year 2022 of IACMAG. Professor Maheshwari served as a Head of Centre of Excellence in Disaster Mitigation and Management and as an Organizing Secretary for 16SEE. He is presently serving as a Vice-President of Indian Society of Earthquake Technology (ISET). He is elected as President, ISET for the term 2023–2025.

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

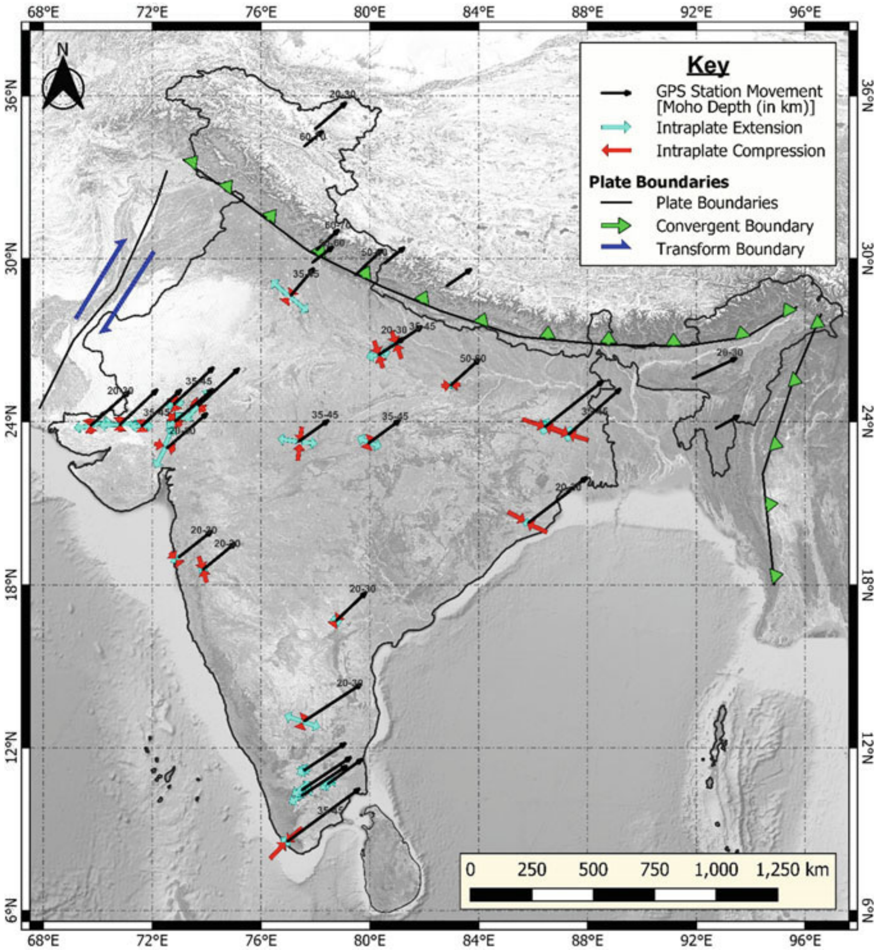

Fig. 1.1 Tectonic movements of India with Moho depth in km (marked in black long thin arrow) and stress direction of extension and compression (marked as a short thick arrow)

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

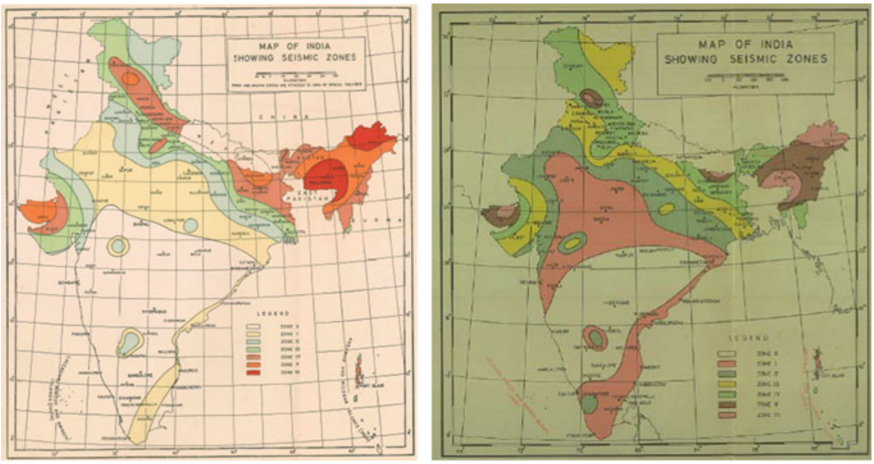

Fig. 1.2 IS 1893 seismic zonation maps published by Indian Standards Institution (IS 1893 [5, 6])

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