Indian Geotech J (February 2021) 51(1):3–49
https://doi.org/10.1007/s40098-020-00465-9

IGC KEYNOTE ISSUE

The Quintessence of 25 Years of Our Contributions to Geotechnical Earthquake Engineering

T.G. Sitharam[1,2]

Published online: 12 February 2021

Abstract An exponential rise in population along with uncontrolled and unplanned urbanization exposed to earthquakes reeks a plenitude of hazard in terms of life and property. Effects, mechanics, and impact of an earthquake in terms of ground shaking, site effects, liquefaction, and landslides had been broadly covered in the past, and the recent developments have catered profound understanding of earthquakes. Our recent studies on ground motion attenuation characteristics, comprehensive seismic hazard analyses, site effects, liquefaction behaviour, seismic microzonation, ground motion analyses, joint time–frequency analysis-based ground motion synthesis, etc., have largely contributed to geotechnical earthquake engineering. Our detailed experimental and numerical works on liquefaction have improved the understanding of liquefaction of sands. Installation of ground motion sensors and monitoring of earthquakes have further supplemented geotechnical earthquake engineering research in the country. Recent surveys on earthquake preparedness and readiness indices have pointed out the urgent need for general awareness, and an action plan towards mitigating and managing the hazard due to earthquakes. This paper discusses the Quintessence of 25 years of the author's contribution to the field of Geotechnical Earthquake Engineering.

Keywords Geotechnical earthquake engineering · Earthquake · Ground motion · Seismic hazard · Microzonation · Seismic design · Time-frequencyanalysis · Soil dynamics · Liquefaction

✉ T.G. Sitharam
tgs@iitg.ac.in; sitharam@iisc.ac.in

1 IIT Guwahati, Guwahati, Assam, India

2 IISc, Bangalore, India

Introduction

An earthquake is the discharge of energy generally owing to tectonic plate movements and rupture of rock along faults. Every year, numerous earthquakes occur around the world causing large losses in terms of lives and property. The majority of the damage due to earthquakes is caused by poorly designed and built structures that have not considered appropriate seismic forces on the structure due to potential earthquakes in the region. Even with seismic design codes and advanced construction practices, recent earthquakes like the 7.8 magnitude Gorkha earthquake in 2015 have caused large losses to life and property. Fatalities around 9000, injuries above 21,000, and financial losses of over 10 billion USD was reported due to the Gorkha earthquake in Nepal [66, 105, 158]. Table 1 presents the major recent earthquakes in India and adjoining regions in the past ten years.

The numbers from Table 1 advocate the need to keep updating the current knowledge and construction practices to aid in curbing these losses. The knowledge of earthquakes, its processes, and dynamics have to be continuously kept in the limelight of research. Further, construction practices in seismically active areas need to be revamped with proper codal revisions and provisions, and strict enactment of these provisions during construction is necessary [117].

Geotechnical earthquake engineering is a very young discipline of civil engineering that considers the geotechnical aspects of the wider discipline of earthquake engineering. Geotechnical conditions are critical to understanding the intensity and pattern of damaging ground shaking at a site. Ground shaking, ground failure from site instability, soil softening especially liquefaction, and lateral spreading are significant earthquake hazards

Table 1 Major earthquakes in India and adjoining regions in the recent past

Date	Location	Magnitude	Casualties
Jan 3, 2017	Tripura	5.7	11
Jan 4, 2016	Manipur	6.7	211
Oct 26, 2015	Hindukush	7.7	2935
May 12, 2015	Kodari, Nepal	7.3	3800
Apr 25, 2015	Gorkha, Nepal	7.8	30,916
May 1, 2013	Kashmir	5.7	93
Sep 18, 2011	Sikkim	6.9	111

that affect foundations, retaining structures, and roads. Geotechnical earthquake engineering is typically concerned with: determining ground motions, analysing effects of soil and local site conditions, liquefaction and liquefaction-related evaluations (settlements, lateral spreading movements, etc.), slope/landslide evaluation, stability of dams, embankments and dykes, design of earth retaining structures, deep and shallow foundation analysis, and underground structures (tunnels, etc.). Numerous aspects of geotechnical earthquake engineering have been researched on and significant contributions are continuously being made by the researchers towards this field to restrain the loss of lives and property in the future to a large extent. Thrust areas towards which major contributions have been made by the author in the past are seismicity analysis, ground motion prediction equations (GMPEs), deterministic and probabilistic approaches in seismic hazard analysis, Liquefaction susceptibility, site response, and site characterization, applications of time–frequency analyses in ground motions, applications of remote sensing in earthquake engineering, seismic microzonation, slope stability, and landslide susceptibility, seismic design of geotechnical structures, vibration isolation, assessment of dynamic behaviour of rocks and soils, experimental and numerical studies to understand liquefaction behaviour, and earthquake preparedness. This paper presents the scientific relevance of these topics in the light of notable contributions towards them from the author.

Overview of Geotechnical Earthquake Engineering

Geotechnical earthquake engineering is a very young discipline that considers the geotechnical aspects of the wider discipline of earthquake engineering. Geotechnical earthquake engineering problems require adequate treatment of geotechnical aspects of the ground and in particular the behaviour of soils under earthquake loading. This includes hazard assessment procedure, evaluation of seismic loads, site investigations, hazard identification, site and soil characterization, assessment of local site effects, liquefaction potential evaluation, analyses, interpretation, and engineering judgement. Consideration of uncertainties in properties of the ground and also other uncertainties in earthquake occurrence is critically important throughout the assessment process. The level of detail and particular features of the assessment procedure in geotechnical engineering should be balanced across all phases of the investigation. They should be appropriate for the scale of the project, the importance of the facilities planned for the site, the level of risk associated with the hazard and potential consequences of failure in terms of loss of life, economic loss, and impacts on communities.

Geotechnical Earthquake Engineering is an area of research involving aspects of geology, seismology, geotechnical engineering, and risk analysis—leading to an assessment of earthquake hazard and restrain the associated risks to endurable limits.

Earthquake studies have revealed that the ground motion intensity is directly related to the type of soil at the site, along with the subsurface stratification. Structures founded on rock and firm soil perform well compared to the structures on soft grounds. Geotechnical aspects like the surface topography, soil type along with the seismological aspects like the frequency of incident wave influences the maximum acceleration experienced on the ground. It was observed from past studies that soft grounds or deposits experience higher peak acceleration than the firm ground. The natural frequency of any soil deposit depends on its composition, groundwater table level, depth of hard rock strata, and other geological features. Further, when different structures are built on the ground, the soil-structure system will have a natural frequency which may be different from that of the soil deposit. When the predominant frequency of an earthquake is close to the natural frequency of the soil deposit or the soil-structure system, there can be resonance, even when the event is of short duration. All these aspects need to be considered for mitigation of earthquake hazards and this demands meticulous research and development in these areas.

The damages due to earthquakes are primarily due to the ground shaking and regional subsidence. The most common secondary effects are soil liquefaction, landslides, and tsunamis to name a few. The geometry and material properties of the subsurface soil, its stratification, and the properties of the bedrock ground motion have a substantial influence on the site amplification. Further, these local site conditions will influence the frequency content, duration, and amplitude of the ground motion. These effects were witnessed during the infamous Niigata, Mexico, San Francisco, and Bhuj earthquakes over the years. Though a considerably new area, substantial advances were made in the field of Geotechnical Earthquake Engineering in recent years. Comprehensive research needs to be further carried out in the areas of liquefaction, ground failure, site response, and the collapse of geotechnical structures. Liquefaction potential, landslide hazard, site response, and site amplification are a few geotechnical aspects of earthquake engineering which requires detailed studies as well. The aim of research and development in the field of geotechnical earthquake engineering should finally aid in the mitigation of seismic hazards by identification of seismic vulnerability and risk, better construction guidelines and town planning, and reliable earthquake preparedness.

A Review of the Geological, Seismological, and Geotechnical Aspects

Earthquake studies of a region require a basic understanding of the geological, seismological, and geotechnical aspects of the region under consideration. The geometry of the subsoil structure, the soil types, and the variation of their properties with depth, the lateral discontinuities, and the surface topography influence the amplification of ground motion and hence the intensity of damage during destructive earthquakes. Site characterization and microzonation studies need to be carried out based on geotechnical, geophysical, and seismological inputs. The local geological conditions have a considerable effect on the ground motion at a given site. The response of different soil types differs when subjected to the earthquake ground motions. Usually, the younger softer soil amplifies ground motion relative to older compact soils or bedrock. Local amplification of the ground is often controlled by the soft surface layer, which leads to the trapping of the seismic energy, due to the impedance contrast between the soft surface soils and the underlying bedrock. The natural frequency of each soil layer depends on the physical properties of soil and the depth to bedrock. For evaluating this, site response studies are to be carried out. The main aim of the site response study is to assess the amplification of ground motion and determination of the natural resonance frequency of the soil.

Several inputs regarding seismicity, geology, and geotechnical characteristics are needed for carrying out a detailed earthquake hazard assessment and zonation of an area [37]. Generally, a seismic study area extending up to 300 km from the boundary of the study area is considered for assessing the hazard at a site. However, if there are any seismic sources which can create a very large earthquake (mega-earthquake), this distance should be increased. The details of the seismic events and the seismic sources need to be identified from this region. The initial estimates of bedrock motions are obtained at the bedrock level using deterministic or probabilistic methods.

The influence of local soil conditions and topography on the earthquake motions need to be analysed to estimate the surface-level ground motions. As the first step for this, the topography (e.g. valley, basin, ridge effects, etc.), and subsurface geomorphology (bedrock depth and geometry of subsurface soil layers) of the region from the geotechnical and geophysical tests, along with water table conditions need to be established. The topography of both the bedrock and the deposited soils has various effects on the incoming seismic waves, such as reflection, refraction, focusing, and scattering. The required soil properties for site characterization are obtained from either geotechnical tests and/or geophysical tests. Broadly, site investigation required consists of arriving at the surface mapping (like local topography, unstable slopes, faults, and floodplains) of the site/region and planning and execution of subsurface investigations. Soil topography needs to be ascertained and the local site effects need to be calculated by considering the topographical effects. The local site effects can be estimated based on the available geotechnical data. If the data available is less, then the assessment can be done using empirical relations.

For assessing the geotechnical data, inputs from field tests like SPT, CPT, MASW, or SASW, and laboratory tests to ascertain the strain-dependent modulus and damping parameters of the soil can be obtained. A list of geotechnical field and laboratory tests to obtain soil parameters are listed in Tables 2 and 3. From these test results, the site characterization as per the National Earthquake Hazards Reduction Program (NEHRP) [74] or Eurocode 8 can be carried out to get the amplification factors using which the hazard can be brought to the ground level. The NEHRP site classes are presented in Table 4.

Further site assessments comprising liquefaction potential and design response spectra are based on the site response and surface ground motions. Geotechnical and

Table 2 List of field and laboratory geotechnical tests

Field tests	Laboratory tests
Standard penetration test (SPT)	Grain size analysis—sieve and hydrometer test
Cone penetration test (CPT)—static and dynamic	Atterberg limits—liquid limit, plastic limit and shrinkage limit tests
Seismic cone penetration test (SCPT)	Natural water content, density, specific gravity tests
Dilatometer test	Permeability tests
Pressuremeter test	Strength Tests—unconfined compressive strength test, direct shear test, triaxial compression tests
Field vane shear test	Consolidation test
Spectral analysis of surface wave (SASW)	Point load strength index
Multichannel analysis of surface wave (MASW)	Dynamic modulus, modulus of elasticity and Poisson's ratio tests

Table 3 List of field and laboratory geotechnical tests for dynamic properties of soil

Field tests	Laboratory tests
Seismic reflection and refraction tests	Resonant column test
Suspension logging test	Bender element test
Seismic cross-hole test	Cyclic triaxial tests
Down-hole and up-hole tests	Cyclic direct simple shear Test
Steady-state vibration test	
MASW and SASW tests	

geological or geomorphological information becomes invaluable in the evaluation of hazards at the ground surface, local site effects, and liquefaction. More accurate the exploration, the greater freedom the planner will have as this will provide a more accurate estimate of hazards. One of the most difficult and controversial aspects of any geotechnical/geophysical investigation is deciding the depth of exploration to be envisaged. This is mostly an art or at best an inexact science. Adverse geology might require more investigations than the average. The investigation spans over several square kilometres to several hundreds of square kilometres. Hence, careful planning of testing program is very essential, to obtain representative site characterization with the minimum number of tests. These data will be of very high importance in evaluating the induced earthquake effects such as site amplification, local site effects, liquefaction susceptibility, and slope stability. The smaller the grid size adopted in a study, the higher will be the accuracy in evaluating the hazard. But this will increase the cost and the manpower requirement for field testing, data collection, and analysis. The accuracy and level of zonation depend mainly on the available database and the quality of the zonation map required. The geotechnical engineer involved should have a reliable judgement on optimizing the extent of these investigations.

Seismicity and Seismic Hazard Analysis

Seismic Hazard Analysis (SHA) essentially estimates the anticipated extent of ground shaking at a particular site during an event, by taking into account the seismic activity of the site and its surroundings. The level of ground shaking is quantified in terms of Peak Ground Acceleration

Table 4 Soil profile type classification for seismic amplification

Soil class	General description	Average V_{s30} (m/s)
A	Hard rock	> 1500
B	Rock	$760 < V_s \geq 1500$
C	Very dense soil and soft rock	$360 < V_s \geq 760$
D	Stiff soil $15 \geq N \geq 50$ or 50 kPa $\geq S_u \geq$ 100 kPa	$180 \geq V_s \geq 360$
E	Soil or any profile with more than 3 m of soft clay defined as soil with PI > 20, w > 40%, and $S_u <$ 25 kPa.	≥ 180
F	Soils requiring site-specific evaluations	

V_{s30} Shear wave velocity of top 30 m soil; *N* SPT blow count; S_u Undrained shear strength; *PI* Plasticity index; *w* water content

(PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), and Spectral Acceleration (SA). Based on these quantified levels of ground shaking, design and construction practices are to be defined for the particular site to ensure a seismically safe structure. Rehabilitation and retrofitting of existing structures are also to be carried out based on these seismic hazard studies and estimated levels of ground shaking. Two SHA techniques in practice are Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA). DSHA considers the geology, tectonics, and past seismic record of the region, regardless of when the event might occur and estimates a conservative result for the closest and worst-case scenario earthquake possible in the region. DSHA is less complex than PSHA as it does not consider the major uncertainties associated with SHA, the location, and the size of the earthquake event [27, 40, 55, 90]. It is based on the Maximum Credible Earthquake (MCE) possible in the region closest to the site, which is basically the greatest earthquake the sources in the region can produce, which can be realistic or anticipated [2, 5, 36, 59]. Due to this reason, the ground motion estimated will be rather conservative and the design based on the same, uneconomical. However, DSHA is adopted for preliminary analysis and design of critical structures like nuclear power plants, dams, etc. [24–26, 31, 39, 42, 64]. However, considering the uncertainties and probability of the size and location of the earthquake makes the SHA more complex. This is done in PSHA, where the influence of all events occurring at a source is considered, as opposed to just the MCE in the case of DSHA [30, 128]. Furthermore, the seismic characterization of seismic sources in the region and the recurrence rate is also to be evaluated. The mean annual rate of exceedance of ground motion considering the uncertainties in location and size of earthquake and attenuation equation is determined in PSHA [14, 29, 53, 58, 65]. As PSHA deals with numerous uncertainties, it is usually adopted in the design and planning of non-critical structures.

A complete and consistent catalog of earthquakes in a region can offer good data for studying the distribution of earthquakes in a region with respect to space, time, and magnitude. Using this complete catalogue, the spatial variation of Gutenberg Richter seismicity parameters a and b can be identified, which can be a major input in probabilistic hazard assessment studies. The parameter a and b depict the productivity of a volume and slope of the Frequency-Magnitude Distribution (FMD), respectively, which represents the seismic activity and relative size distribution of earthquake events in the region [41]. Mapping the spatial distribution of these parameters can be used to express the seismotectonics and earthquake size distribution of the region and large variations in these parameters represent the heterogeneity of the region in all aspects [126]. Kolathayar et al. [52] quantified the variability in the seismic activity rates across the whole of India and adjoining areas using historical and instrumental earthquake databases compiled from various sources. A list of 203,448 earthquakes (including aftershocks and foreshocks) occurred in the region covering the period from 250 BC to 2010 AD was compiled, declustered, and homogenized using regional magnitude conversion relations. Using this database, the spatial variation of the seismicity parameters of the country was estimated and reported. Figure 1 shows the spatial variation of a value from a declustered catalog considering events within a radius of 300 km from the center of each grid point.

Identification and characterization of seismic sources are essential inputs for SHA. A complete and consistent catalog of earthquakes in a region can offer good data for studying the distribution of earthquakes with respect to space, time, and magnitude. The tectonic framework of seismically active regions can be complex and vary spatially. This necessitates identifying different regions of similar seismicity [127]. An updated earthquake catalog that is uniform in moment magnitude for India and the adjoining area for the period from 250 BC until 2010 was developed by Kolathayar and Sitharam [52]. Region-specific magnitude scaling relations for the country and adjoining areas were developed, which facilitated the generation of a homogenous earthquake catalog for the region. Using this catalog, the completeness of the data was estimated, using which the Gutenberg–Richter seismicity parameters were calculated. Based on the event distribution

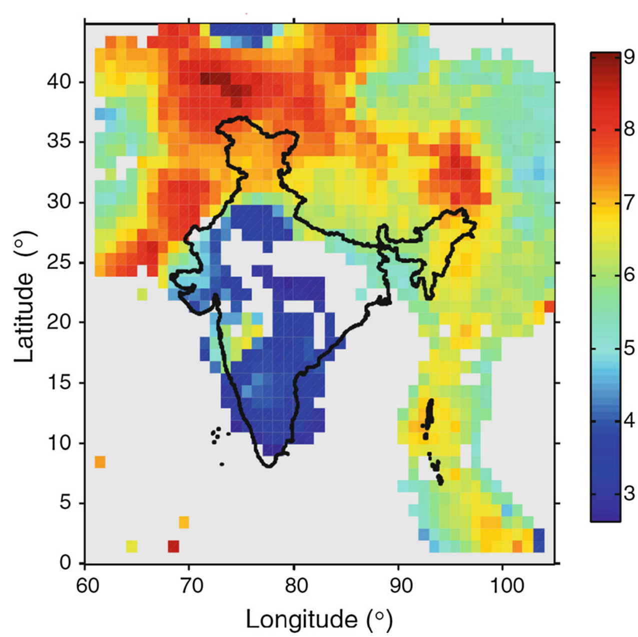


Fig. 1 Spatial variation of a value in and around India [52]

and the seismicity parameters *a* and *b*, the whole area was delineated into 104 regional seismic source zones as shown in Fig. 2. Further, a separate catalog for each of these zones was developed and seismicity analysis for each zone was performed after estimating the cut-off magnitude. The coordinates of these source zones and the estimated seismicity parameters *a*, *b*, and *M*max could be directly inputted into probabilistic seismic hazard analysis.

In a recent study by Monalisha and Sitharam [72], a focussed attempt was made to assess the seismic hazard parameters (*a*, *b* and M_c) and their spatial variation in western Himalaya, central Himalaya, and Indo Gangetic plain areas—one of the most seismically active regions in the country. Using the maximum likelihood estimation method, the spatial variation of seismicity parameters was analysed for the complete catalogue period, after dividing the whole region into small grids of 0.5° × 0.5°. Large variation of the seismicity parameters was observed from the west to the eastern Himalayas and based on the same, the region was divided into 5 regional source zones as shown in Fig. 3.

Extensive studies have been made in SHA in the past by the author and the works are summarized under two further sections DSHA and PSHA as following.

Deterministic Seismic Hazard Analysis

The ground motion for design at a location can be estimated by carrying out SHA using deterministic and probabilistic approaches. Deterministic Seismic Hazard Analysis (DSHA) can be carried out using the declustered homogenized earthquake data, suitable GMPEs, and apt selection of source models. It is a rather straight forward approach using the seismic activity and geologic setting of the site to identify the largest earthquake each source can produce, irrespective of time. This largest possible earthquake-related to a source from the history or assumed tectonic action is called the Maximum Credible Earthquake (MCE). This approach provides the most critical earthquake scenario, considering the magnitudes of the events from various sources like point and linear sources within a selected buffer area from the regions under study. The chance of occurrence of a particular event within the expected lifespan of the structure is not considered here, making the results conservative and the design uneconomical [5, 51, 136]. Also, the location and magnitude uncertainties involved with an event are not considered in DSHA. This can be addressed using the Probabilistic hazard analysis. However, the results obtained from DSHA are used for important structures like nuclear reactors, dams, coastal reservoirs, major bridges, tunnels, etc. The idea of DSHA can be represented in four major steps, like identification of sources, estimation of shortest distance from the source to site, estimation of PGA using GMPEs for each identified source, and determination of hazard corresponding to the maximum level of ground motion estimated from the previous step.

Sitharam et al. [130] adopted DSHA for estimating the Peak Horizontal Acceleration (PHA) of Bangalore City. For identifying the faults, lineaments, and shear zones in

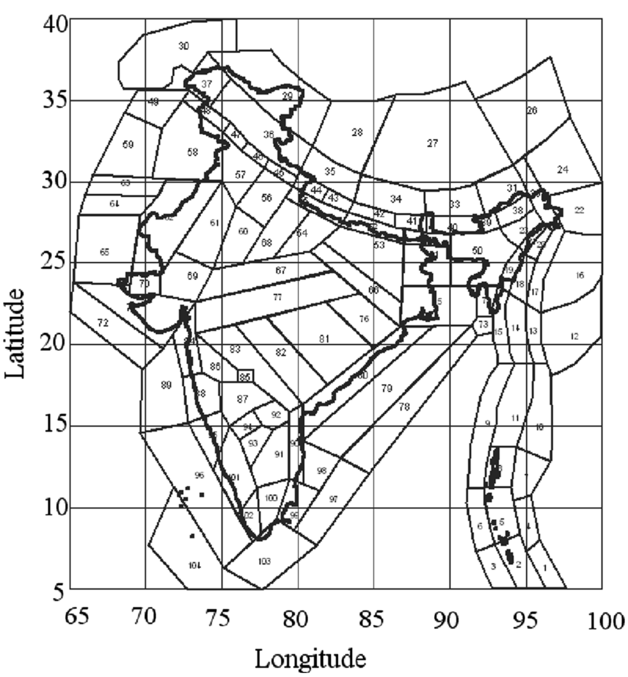


Fig. 2 Identified regional seismic source zones in and around India [52]

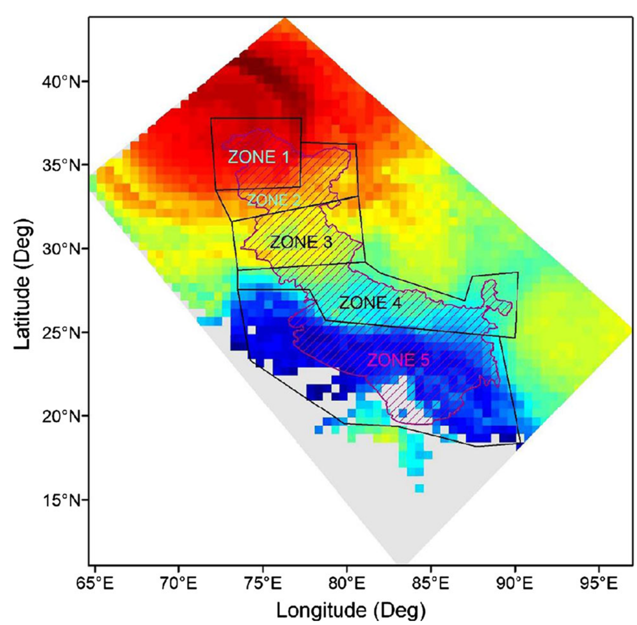


Fig. 3 Variation of seismicity parameter *a* and delineation of seismic source zones for Himalayas [72]

and around the study region, remote sensing data were used and interpreted by Sitharam et al. [131] and Sitharam et al. [133]. In these studies, DSHA was carried out by considering the historic earthquake, assumed subsurface fault length, and point source synthetic ground motion generation models. Remote sensing data were used to identify the linear sources within the buffer area around the study region. The Mandya–Channapatna–Bangalore lineament was identified as a vulnerable source for Bangalore and PHA was estimated considering the MCE in the region using regional GMPEs and was found to be 0.15 g. Further, SMSIM-FORTRAN programs were used to simulate ground motions for estimating the PHA and PHA of 0.146 was estimated in the Bangalore City. The study recommended that the city is a seismically moderately active region. As part of this work in the year 2005, five strong-motion accelerographs and two borehole sensors have been installed at different locations in Bangalore. The rock level PHA in these studies had been calculated using the rock depth information from geotechnical data from a total of 653 boreholes. The methodology and PHA estimated in these studies had been used as the basis for further advanced studies on-site effects and microzonation by Sitharam and Anbazhagan [112], Anbazhagan and Sitharam [3], Sitharam and Anbazhagan [113], Sitharam et al. [138], and Anbazhagan et al. [14], which will be further discussed in upcoming sections.

Kolathayar [140], carried out a comprehensive seismic hazard analysis of India and its adjoining regions. DSHA and subsequent macrozonation of the region were reported considering linear and point source models. The homogenized, declustered earthquake catalog developed in the previous studies [52, 56] was used for generating the point sources. The linear sources were identified from SEISAT 2000. Three GMPEs each for 4 major tectonic provinces, shield region, active tectonic region, subduction intraslab region, and subduction interface region were used within a logic tree framework to address the epistemic uncertainties in hazard estimation. Bedrock level deterministic hazard maps for Peak Ground Acceleration (PGA) and Peak Spectral Acceleration (PSA) at 0.1 s were generated for maximum magnitude earthquakes estimated using various methods using various GMPEs for different tectonic provinces with and without using the logic tree approach and compared [55]. Figure 4 shows the reported spatial variation of bedrock level PGA in and around India.

Later, this study was advanced by estimating the surface-level PGA values from the bedrock level PGA estimated earlier by Sitharam et al. 2010 [134], based on four different site classes suggested by NEHRP [74]. The PGA values at ground level were estimated for all the four site classes and hazard maps developed based on a nonlinear site amplification technique considering the site effects. These studies showed that the seismic hazard is moderate in peninsular shield (except Kutch region of Gujarat), but the hazard in the north and northeast India and Andaman–Nicobar region is very high. The PHA values obtained in this study for most parts of the country are higher than what is specified by BIS-1893:2002.

Sitharam et al. [125] and Sitharam et al. [119] presented a deterministic and probabilistic seismic hazard map of the Indian state of Karnataka and developed response spectra and hazard curves for the major cities in Karnataka. Apart from referring to seismotectonic atlas (SEISAT 2000) for identifying faults and fractures, major lineaments in the study area were also mapped using satellite data. An updated declustered and homogenized earthquake catalogue was compiled and, considering point sources and linear sources, DSHA was carried out using three different GMPEs in a logic tree framework. The hazard map developed is shown in Fig. 5. Higher PGA values, in the range of 0.3–0.4 g was observed for some regions in north Karnataka, which is much higher than the values predicted in past studies. The analysis also showed moderate to high hazard values in the southern Konkan coast and low hazard value for interior regions of Karnataka.

Based on the bedrock level PGA estimated for Karnataka, the surface-level PGA was further estimated considering site effects, for four different site classes suggested by NEHRP. The PGA values at ground level were estimated for all the four site classes and hazard maps were developed based on a nonlinear site amplification technique [69]. James and Sitharam [47] further carried out micro and macro zonation for different regions in

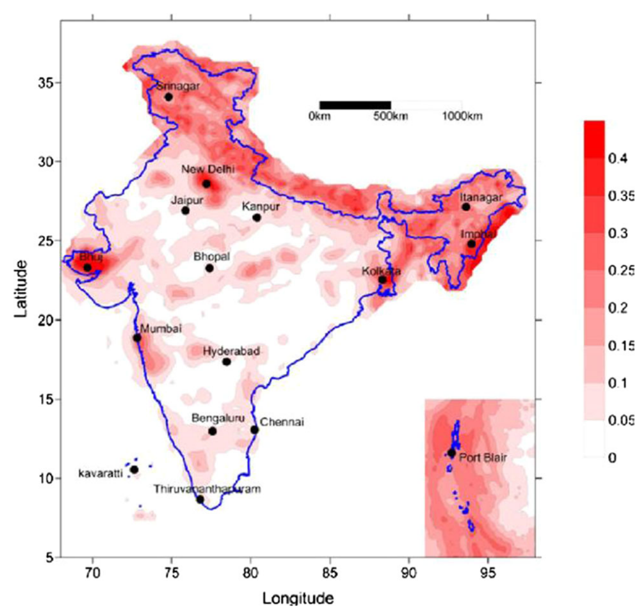


Fig. 4 Spatial variation of bedrock level PGA in and around India [56]

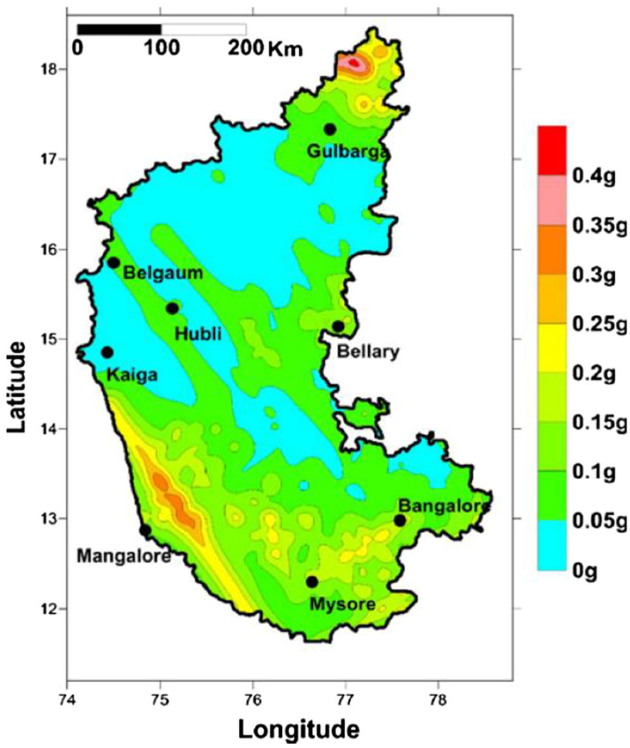


Fig. 5 DSHA map showing bedrock level PGA for Karnataka [119]

peninsular India; micro zonation for a nuclear power plant site at Kalpakkam and macrozonation of the whole state of Karnataka, considering various parameters like seismic hazard and liquefaction potential. Digital Elevation Models (DEMs) were used for site characterization based on topographic slopes and NEHRP amplification factors were used to estimate the ground-level PGA from the bedrock level PGA.

Vipin and Sitharam [149] using a similar methodology, reported the DSHA-based PHA and SA hazard maps for peninsular India using a logic tree approach to address the epistemic uncertainties in the evaluation of hazard. Three GMPEs and two source models, linear and point were considered for the study, and bedrock level PHA and SA for 1 Hz and 10 Hz for both source models were estimated after dividing the whole region into grids of size 0.1° × 0.1°. In this study, to account for the uncertainty in SA prediction, the 84th percentile was considered. The PHA and SA values for the study area were calculated in this study for both the mean and 84th percentile. Using the nonlinear amplification technique based on soil types as reported in the previous studies, this bedrock level hazard was brought to the ground surface and reported as well. Further, the response spectra for major south Indian cities were also presented. Figure 6 represents the mean bedrock level PHA estimated from both source models. The results showed the highest values of 0.5 g around the Mumbai-Koyna region.

Kumar [1] carried out a detailed seismic assessment and microzonation including field studies for the city of Lucknow. A buffer area of 300 km was considered around the study region and seismic sources—linear and point sources within the buffer region were considered for DSHA. Three different GMPEs including a region-specific GMPE was used by assigning them different weights for PGA estimation. Different focal depths were considered for events above and below moment magnitude (M_w) 7 in the study and the whole area was divided into grids of size 0.015° × 0.015° for PGA estimation. The bedrock level DSHA map of Lucknow city centre and the DSHA-based response spectra were also developed in this study. Further, PSHA hazard maps and hazard curves for the region was also developed and presented in this study, which will be elaborated in later sections. Figure 7 shows the DSHA map for Lucknow.

Northeast India is one of the most seismically active regions in the world with yearly more than seven earthquakes of magnitude 5.0 and above on average. Considering the high seismicity, a comprehensive Seismic Hazard Assessment of two north east Indian states, Tripura and Mizoram, along with microzonation of Agartala and Aizawl cities was carried out by Sil [19]. Sitharam and Sil [104] reported a deterministic and probabilistic SHA at bedrock level for Tripura and Mizoram. An earthquake catalogue from 1731 to 2011 was used in the analysis and based on the seismicity, tectonic features, and fault rupture mechanism, this region was divided into six major subzones. Two different GMPEs were validated using observed PGA from an actual recorded event and used in the hazard assessment. The maximum magnitude was

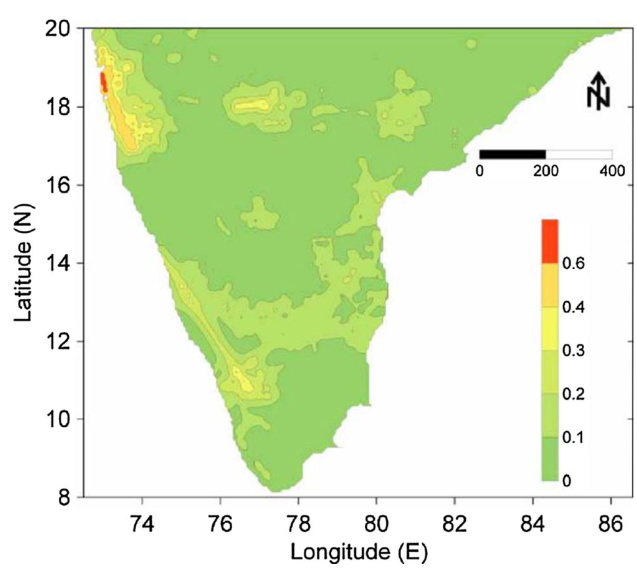


Fig. 6 Spatial variation of mean bedrock level PHA(g) values for South India [149]

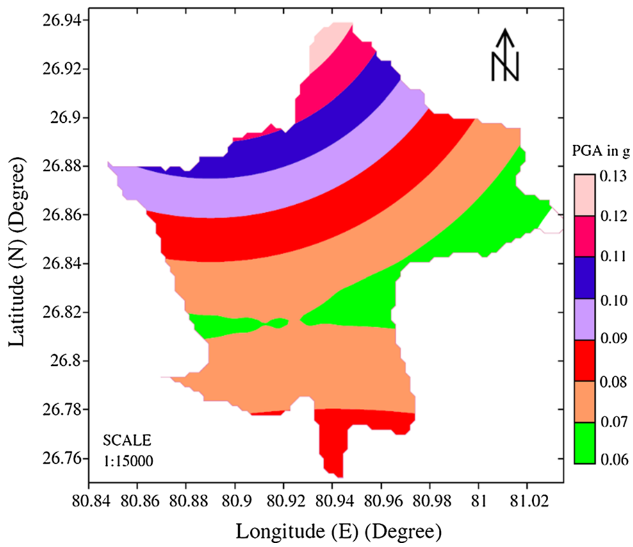


Fig. 7 DSHA map of Lucknow urban centre [61]

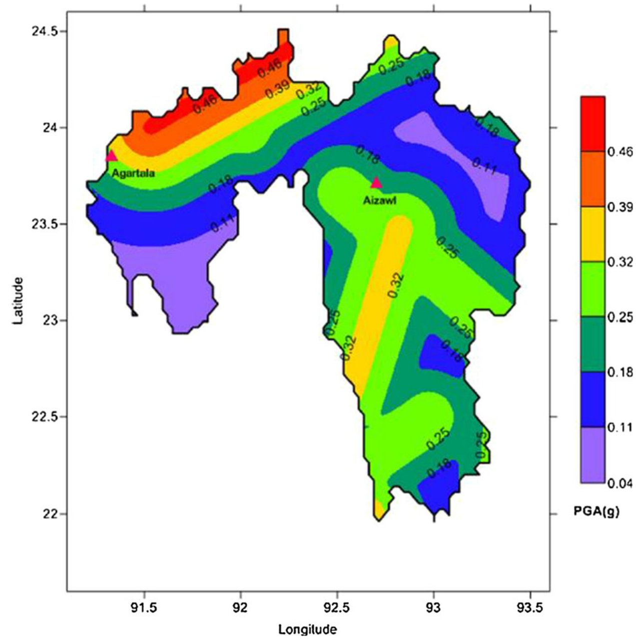


Fig. 8 DSHA map of Tripura and Mizoram states [104]

estimated using different approaches and assigned to each linear sources, using which DSHA was then carried out. In DSHA, the higher PGA values were observed towards the north of Tripura having PGA 0.39–0.53 g in N–W direction; whereas lowest hazard ranges were found in the south part of Tripura having PGA 0.04–0.11 g as shown in Fig. 8.

Probabilistic Seismic Hazard Analysis

The major uncertainties associated with SHA are the location and size of the earthquake event, which makes the analysis more complicated. DSHA does not consider these uncertainties and is comparatively simpler and a conservative approach to SHA. Probabilistic Seismic Hazard Analysis (PSHA) addresses these issues and paves the way to consider these uncertainties by ascertaining, relating, and merging them and providing a comprehensive representation of the truly complex seismic hazard [53, 58, 62, 147]. PSHA combines the effect of earthquake possibility at any location along with a source, covering the uncertainties in the location of the event, event magnitude, source to site distance, and GMPEs, as opposed to the minimum distance to maximum magnitude event in DSHA. As PSHA deals with numerous uncertainties, it is usually adopted in the design and planning of non-critical structures. The probabilistic hazard estimation is carried out assuming that the occurrence of an event in a seismic source is expected to have a Poisson distribution. A simple representation of the idea of PSHA can be explained as four major steps like identification of sources, estimating the seismicity parameters considering the recurrence relation for each source, addressing the uncertainty in GMPE, and estimating the PGA for each source.

Various methodologies for PSHA had been attempted by the author in the past, using different source models [55, 114]. Different source models like linear sources, areal sources, and zone-less approach had been attempted. Several PSHA studies have been carried out in the past, covering most of the Indian subcontinent and the major cities. Major findings from those studies are discussed here. A PSHA of Bangalore, south India, was carried out by Anbazhagan et al. [11] considering sources and earthquake events within a source zone of 350 km around Bangalore, and the seismicity parameters were estimated using Gutenberg Richter relationship using a complete event catalogue. *b* values up to 0.98 were observed in the region, which was higher than what was reported in the previous studies [18]. For a grid size of 0.5° × 0.5° and considering six seismogenic sources, the mean annual rate of exceedance and cumulative probability hazard curve for PGA and SA was developed along with a PGA hazard contour for 10% Probability of Exceedance (POE) in 50 years and was presented. Further, Uniform Hazard Response Spectrum (UHRS) with 5% damping for Bangalore was also generated for a 10% probability of exceedance in 50 years for bedrock condition. Bedrock level PGA of 0.17–0.25 g was obtained for 10% POE in 50 years while carrying out PSHA using the region-specific GMPE by Raghukanth and Iyengar [159], which was higher than the values reported by other researchers in the past. The hazard contour for Bangalore obtained is presented in Fig. 9.

Based on the above work PSHA was further reported with an emphasis on the local site conditions by Anbazhagan et al. [4]. From the extensive Multichannel

Analysis of Surface Waves (MASW) field tests carried out, the study area was generally classified as NEHRP class D, based on which hazard curves of the mean annual rate of exceedance for peak ground acceleration and spectral acceleration have been generated. Considering local site effects, the UHRS with 5% damping for Bangalore was generated for a 10% probability of exceedance in 50 years for bedrock condition. The peak ground acceleration (PGA) value of 0.121 g at the bedrock level and value of 0.35 g considering the local site condition for the Bangalore region was observed. This work was later extended considering specific site classes of the city, ranging from NEHRP site classes B, C, and D, and the mean annual rate of exceedance and cumulative probability hazard curve for SA was presented by Anbazhagan et al. [15] and Anbazhagan et al. [17]. The quantified hazard values in terms of SA for short period and long period were mapped for rock, site class C, and D with a 10% probability of exceedance in 50 years, along with a 5% damped surface-level UHRS which is represented in Fig. 10. These spectral acceleration and uniform hazard spectrums could be used to assess the design force for important structures and also to develop the design spectrum for the city. To address the epistemic uncertainties in hazard estimation, the above study was approached using a logic tree approach later by Sitharam and Vipin [106]. Different methods of site classifications were also reviewed in this study and the local site effects were considered. The surface-level PGA and UHRS were developed for four different site classes for the city of Bangalore.

Vipin [51] carried out extensive studies on SHA using both approaches for peninsular India. Vipin et al. [150] presented a PSHA of peninsular India using the above methodology using a region-specific GMPE by Raghukanth and Iyengar [159]. A complete, declustered, and homogeneous earthquake catalogue was prepared and a seismotectonic map was developed considering all linear sources within a buffer area of 300 km radius. The study area was divided into grids of 1° × 1° and the seismicity parameters. Rock level PHA and SA values at 1 s corresponding to 10% and 2% POE in 50 years were estimated for all these grid points. 5% damped UHRS at rock level for 10% and 2% POE in 50 years for different South Indian cities were also presented. Considering four different site classes, surface-level PGA was also calculated for entire South India, using which the PGA values at any site in South India based on site class could be estimated. The rock level PGA obtained is represented in Fig. 11.

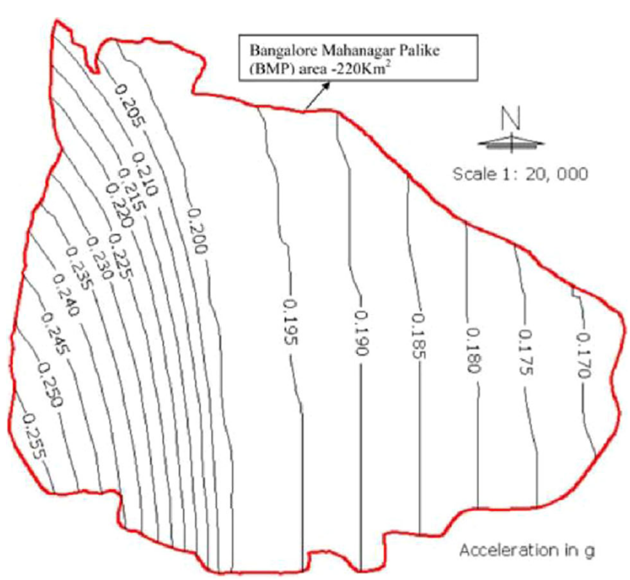


Fig. 9 Rock level PGA contours for 10% POE in 50 years for Bangalore [3]

Later, a logic tree approach to the above problem of PSHA of peninsular India was adopted by Sitharam and Vipin [107], considering two source models, linear and areal, and considering three different GMPEs to address the uncertainties in the usage of a single GMPE. Spatial variation of the seismicity parameters was reported and the region was divided into 5 source zones using which PSHA was carried out within the logic tree framework shown in Fig. 12a. Rock level PHA and short and long period SA were reported for 10% POE in 50 years, along with the rock level UHRS for major south Indian cities, as shown in Fig. 12b. Another attempt on the PSHA of peninsular India was carried out using a different logic tree approach by Vipin and Sitharam [147]. Two different types of seismic sources, linear and areal, were considered in the study to model the seismic sources in the region more precisely. To appropriately account for the attenuation characteristics of the region, three different attenuation relations were used with different weightage factors. The whole area was divided into five seismogenic source zones based on their GR seismicity parameters. In the logic tree, the hazard was estimated using three GMPEs considering these five source zones (with weightage 0.6) and considering the whole region as a single zone (with weightage 0.4), and taking into consideration two different source models, linear and areal. Bedrock level PGA, SA for 1 Hz and 10 Hz, were reported for 2% and 10% POE in 50 years. Considering different site classes (A–D), the bedrock level PGA estimated was brought to the surface level and reported for both the POE considered. Further, UHRS for cities like Mumbai and Chennai were developed and presented.

Using a similar approach using a logic tree, considering two source models, two approaches for maximum magnitude estimation, and three GMPEs, the PSHA of the south Indian state of Kerala was carried out by Kolathayar and Sitharam [54]. Bedrock level PGA for return periods of 2475 years and 475 years and SA for short and long

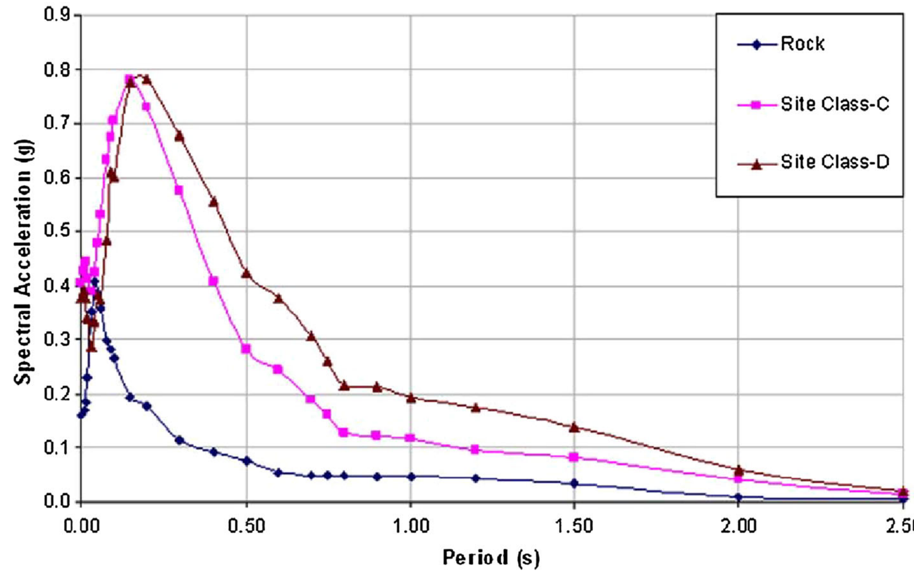


Fig. 10 5% damped UHRS for bedrock, Site C and Site D with 10% probability of exceedance in 50 years for Bangalore [17]

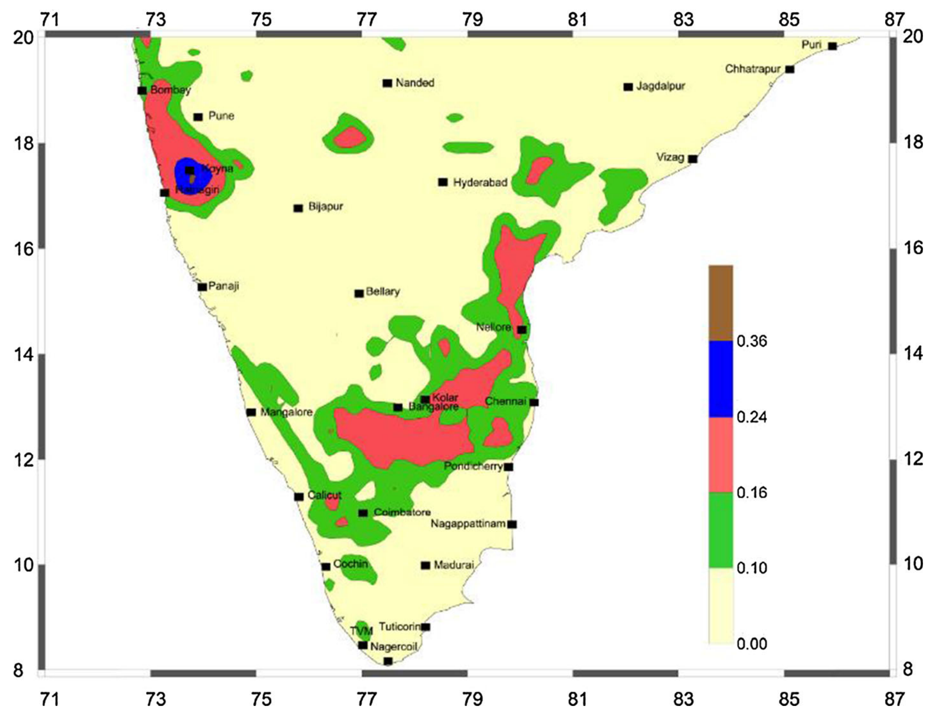
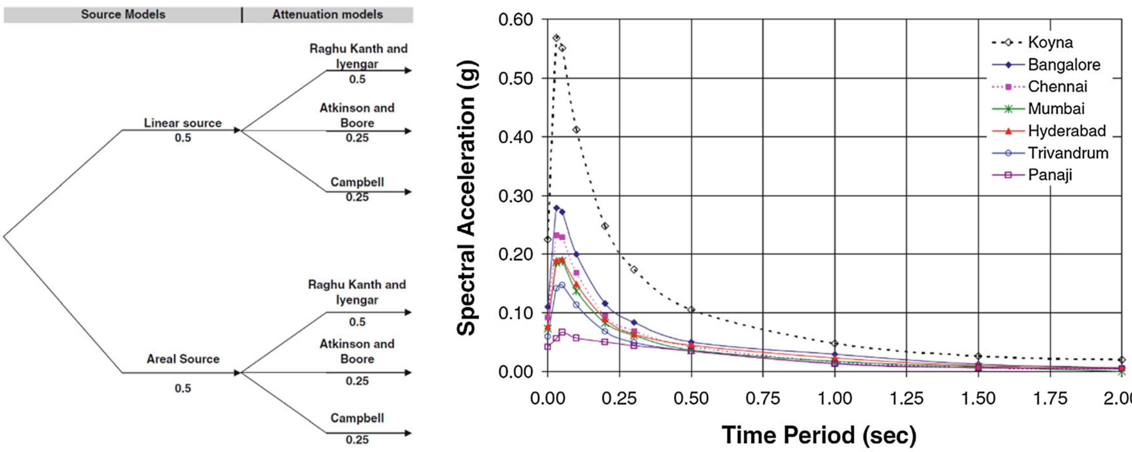


Fig. 11 Rock level PHA(g) for 10% POE in 50 years [150]

periods for 10% POE in 50 years have been reported. The study reported low seismicity in this stable peninsular region, though with PHA up to 0.1 g for 10% POE around the south and central Kerala.

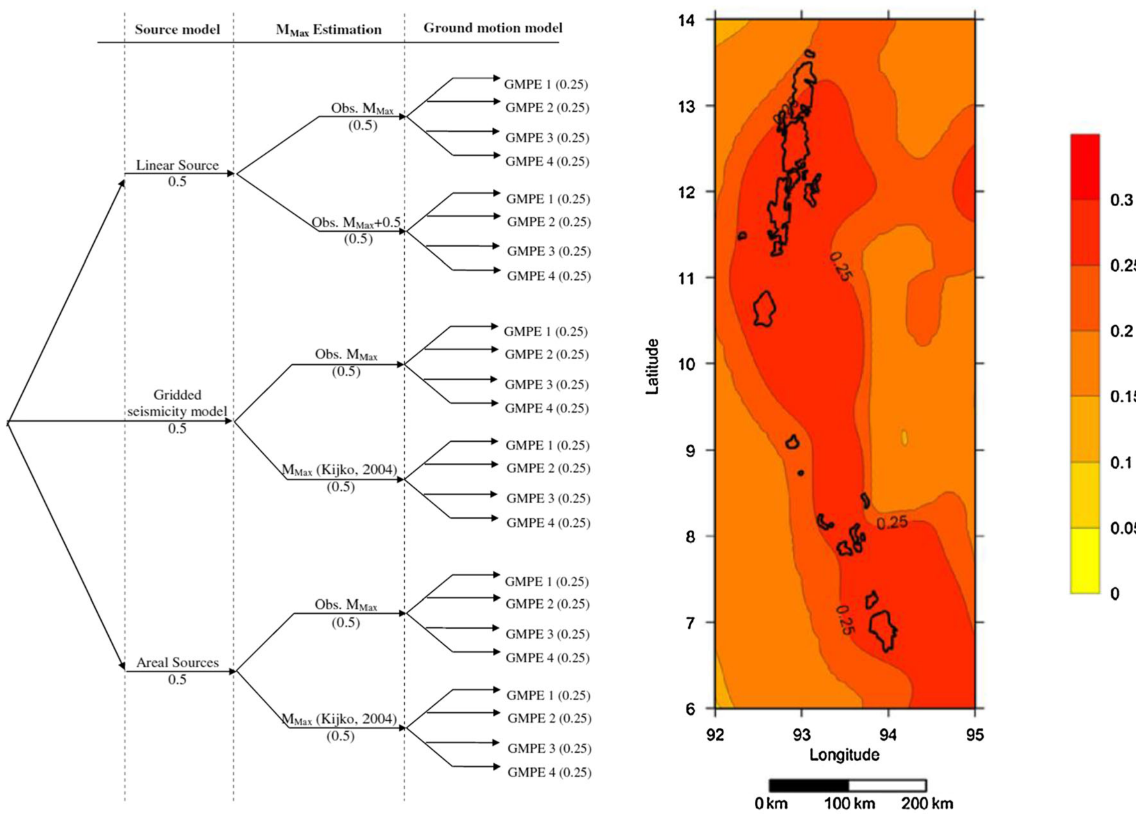
A comprehensive PSHA of the Andaman and Nicobar region of India had been attempted by Kolathayar and Sitharam [53]. An elaborate logic tree approach was considered in this study, to explicitly account for epistemic uncertainty by considering alternative models (source models, maximum magnitude, and attenuation relationships as shown in Fig. 13a. Three different GMPEs, two different approaches to estimate the maximum magnitude, and three different source models like linear sources, gridded seismicity models, and areal sources were considered in this study. Using a complete earthquake catalogue, the seismicity of the region was defined using the GR parameters and was delineated into 11 seismic source zones. PSHA was then carried out to estimate the bedrock level PGA and SA for 0.1 s and 1 s for both 2% and 10% POE in 50 years. Figure 13b represents the hazard contours representing the bedrock level PHA up to 0.3 g, for 10% POE in 50 years.



(a) (b)

Fig. 12 **a** Logic Tree Framework adopted. **b** UHRS for important cities of South India for 10% POE in 50 years [107]

Sitharam and Kolathayar [115] attempted a PSHA of India and adjacent regions [140] considering areal sources and four different GMPEs by dividing the country into three broad tectonic provinces, Tectonically active shallow crustal region, subduction zones and the stable continental region. Regional seismic source zones delineated in Kolathayar and Sitharam [52] represented in Fig. 3 were used for PSHA. The study area was divided into small grids of size 0.1° by 0.1° and the PHA and SA for periods 0.1 s and 1 s were estimated and contour maps showing the spatial variation of the same were presented for 2% and 10% POE in 50 years. PGA values around 0.75 g were detected in the Himalayan region for a return period of



(a) (b)

Fig. 13 **a** Logic tree approach used in the study. **b** Hazard map for bedrock level PHA for 10% POE in 50 years [53]

2475 years. Figure 14 represents the bedrock level PHA estimated for 2% POE in 50 years in the study.

As a continuation of the studies on SHA of North-East states of Tripura and Mizoram by Sil [19], PSHA of the regions were also presented by Sil et al. [96]. A buffer area of 500 km around the study area was considered and an earthquake catalogue of events between 1731 to 2010 was developed, homogenized, and declustered. Based on the GR parameters, the area was divided into six seismogenic sources and two GMPEs applicable for subduction zones were adopted. The maximum magnitude for each of the identified linear sources was estimated and was used for PSHA. Hazard curves were developed and bedrock level UHRS for 2% and 10% POE in 50 in years for the capital cities of these states, Agartala and Aizawal was reported along with the spatial variation of rock level PGA. PGA up to 0.2 g was reported for Agartala and 0.17 was reported for Aizawal cities which were comparable to past studies for the region. Bedrock level PGA of the region and UHRS of Agartala city estimated in the study are shown in Fig. 15a, b, respectively.

Based on the experiences from PSHA and applications of the logic tree, Sitharam et al. [135] carried out a comprehensive PSHA of India using the extensive logic tree approach as shown in Fig. 13a [53] and seismic source zones as shown in Fig. 3, [52] and bedrock level PHA was estimated for India. In this study, site characterization of the whole country was carried out based on shear wave velocity and site classes as per NEHRP, based on the slope maps developed using the DEM obtained from remote sensing data, based on past correlations. Using this method considering ground slope as a proxy to site class, the bedrock level PHA was brought to the ground surface, and

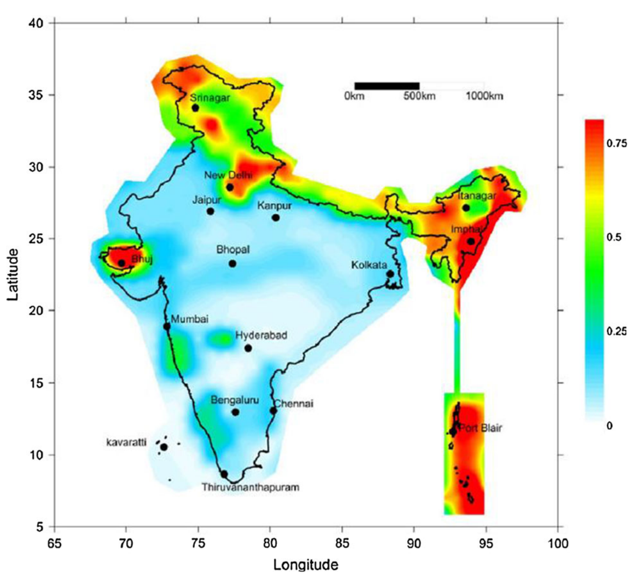


Fig. 14 Bedrock level PHA estimated for 2% POE in 50 years [115]

spatial distribution of PHA was presented. The surface-level PHA for India for a return period of 475 years obtained in this study is presented in Fig. 16.

Monalisha [67] carried out a comprehensive SHA of North India considering local site effects. As a part of this, Monalisha et al. [73] presented an SHA of the Uttarakhand state of India, which is a highly populated state that lies at the foothills of the North Himalayas. An updated, complete, homogenized, and declustered earthquake catalogue was used for the analysis considering two source models and three GMPEs in a logic tree framework. The study region was divided into grids of size 0.1°x0.1° and the bedrock level PGA, and SA for 0.1 s and 1 s were estimated for POE of 2% and 10% for a period of 50 years. For 2% POE, PGA up to 0.55 g, and for 10% POE, up to 0.35 g was estimated at the bedrock level, whereas considering the IS codal provisions, a Zone factor of 0.12 to 0.18 are recommended for the region. Using DEM and slope map as a proxy for site class, the bedrock level PGA was brought to the ground surface for four site classes A to D, as discussed earlier using data obtained from Remote Sensing SRTM images. The surface-level PGA was observed to be most amplified for site class A and least for class D. Figure 17 shows the SA estimated for 2% POE in 50 years for period 0.1 s.

Sil et al. [97] assessed various probabilistic models for forecasting earthquakes in India's most seismically active region—the Northeast. Using an updated earthquake catalogue, the probability of occurrence of an earthquake of $M_w > 6$ in this region was examined. Based on the different tectonic features and seismogenic factors, the catalog was divided into six different seismic regions, and using three different models, Weibull, Lognormal and Gamma distribution models, the probability of occurrence was projected. The logarithmic probability of the likelihood function for all six seismic regions and the entire northeast for all three stochastic models was estimated, where, a large likelihood function represents a better model and vice versa. It was observed that for forecasting magnitude size, lognormal was the most suited for most of the sources; however, different models are suited for different seismic zones. The Weibull, Gamma, and Lognormal models showed the highest, intermediate, and lowest conditional probabilities among the models. It was concluded from the study that the Indo-Burma Range and Eastern Himalaya had a high probability of occurrence in the 5 yr period 2012–2017 with > 90% probability. Looking back now, there was an M_w 6.7 earthquake in Imphal, Manipur, Northeast India on 4th January 2016, and it was felt in Burma and Bangladesh as well. There was also another event on 3rd January 2017 of M_w 5.7 which hit Tripura in North East India.

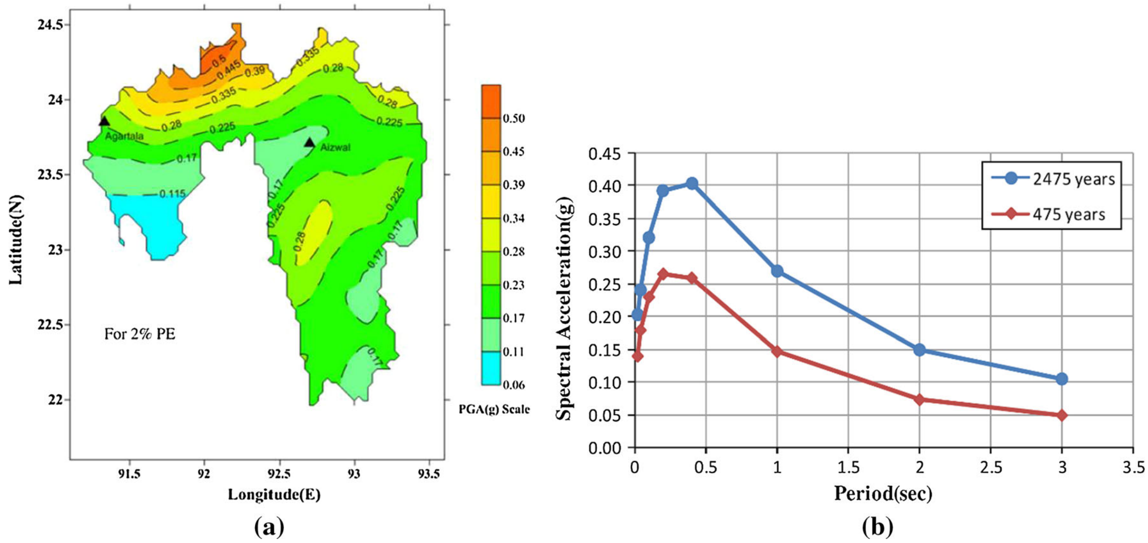


Fig. 15 **a** Bedrock level PGA for 2% POE in 50 years. **b** UHRS for Agartala City for different return periods [96]

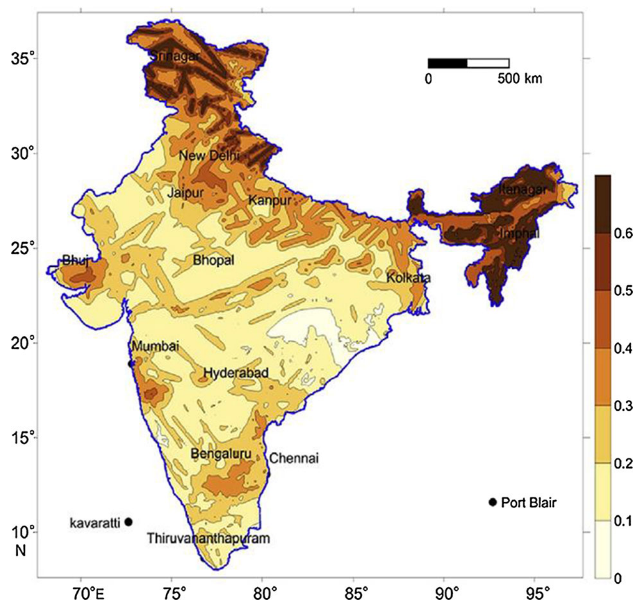


Fig. 16 Surface-level PHA for India corresponding to 10% POE in 50 years [135]

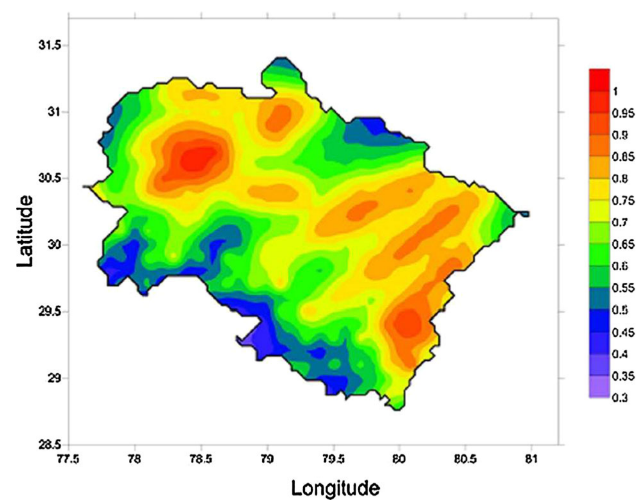


Fig. 17 SA estimated for Uttarakhand for 2% POE in 50 years for period 0.1 s [73]

Ramkrishnan et al. [85] developed a combined map of Land Use and probabilistic seismic hazard for the developing city of Mangalore in south Karnataka, India. The remote sensing techniques were applied to estimate the land use dynamics of the region and the rise in uncontrolled urbanization and reduction in open spaces and green patches were reported. A PSHA map was generated considering two source models—point and gridded seismicity models, considering a buffer area of 300 km around Mangalore and using three different GMPEs. The highest PGA estimated off the three GMPEs were reported and the hazard contours were overlain on the land use map to obtain the combined land-use-PSHA map as shown in Fig. 18. It could be observed from the figure that the most urbanized regions had PGA varying from 0.0498 to 0.1087 g, which puts them at high risk, considering the level of urbanization and a large number of tall and old structures in the city. This method helps to visually identify highly urbanized regions along with the spatial distribution of PGA, thereby enabling to judge the seismically risky areas in the study region.

Deterministic and Probabilistic hazard analysis of the whole country had been carried out considering numerous source models and GMPEs. Uncertainties in GMPEs, location, and hypocentral distance have been considered in the probabilistic approaches and epistemic uncertainties have been addressed using logic tree approaches in most of

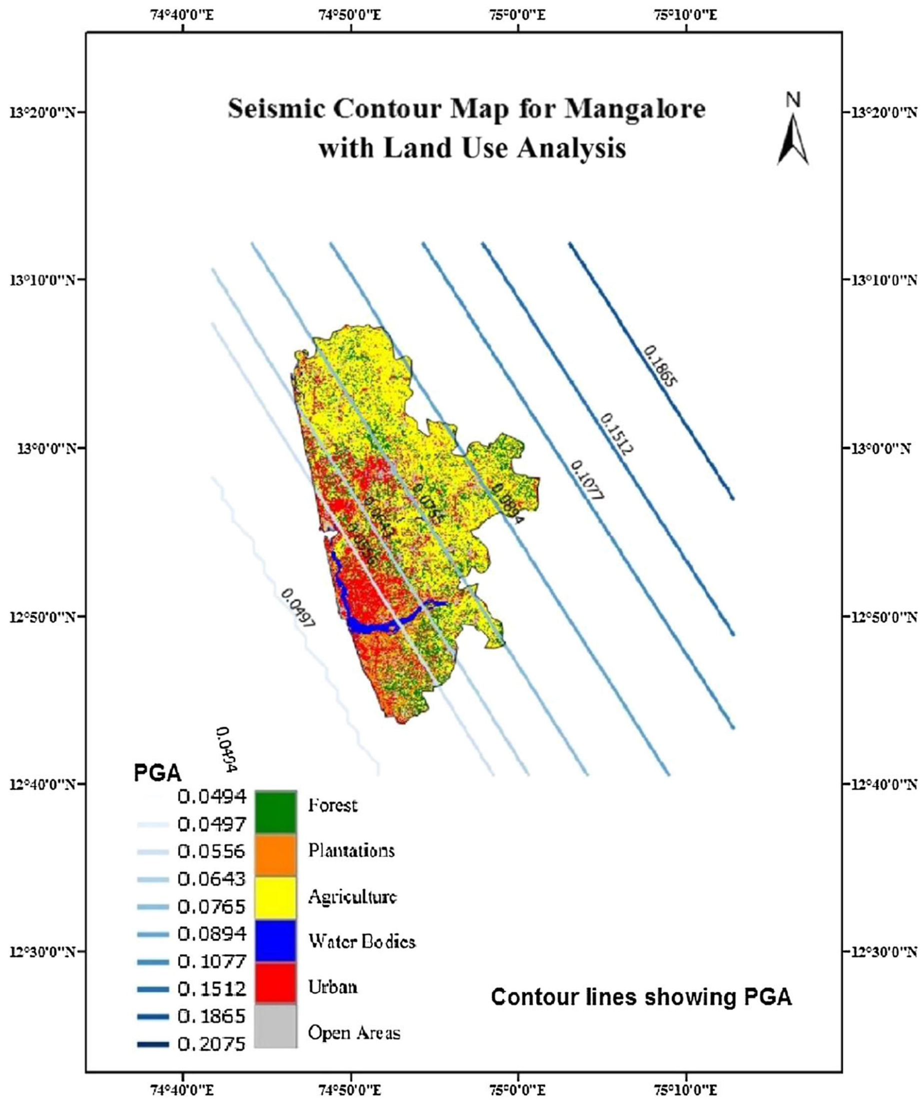


Fig. 18 Seismic Contour Map for Mangalore with Land Use Analysis [85]

the studies. SHA for the whole country and south India have been done on a macro-level based on the amplification factors estimated based on ground gradient, surface-level PGA was also estimated and reported. SHA of major and vulnerable cities like Lucknow, Agartala, Bangalore, and Mangalore, and states like Karnataka, Tripura, Mizoram, Uttarakhand, etc., have been covered using deterministic and probabilistic approaches, considering various uncertainties. UHRS has further been developed for highly hazard prone cities like Agartala, and highly populated major south Indian cities like Mumbai, Bangalore, Chennai, etc.

Ground Motion Prediction Equations

Ground Motion Prediction Equations (GMPEs) or Attenuation relations are empirical equations to estimate the level of ground movement during an earthquake event at a particular site, considering the influential source and event parameters. The parameters which influence the level of ground shaking at a site are the event mechanism, site characteristics at the source, properties of the propagation path, and the local soil or site geology which further affects the wave attenuation or amplification. Simple forms of GMPEs usually contain the ground motion parameters as a function of magnitude and distance, and more advanced GMPEs developed using extensive recorded and site data have further parameters like local site characteristics, fault and rupture characteristics, etc. Most of the regional GMPEs developed for the Indian subcontinent are of simple forms due to severe constraints in lack of reliable data, and developed countries with well-defined and dispersed strong-motion recording network have more complex GMPE with site characteristics and rupture characteristics, recent ones being called the Next Generation Attenuation (NGA) relations [160–162]. They are one of the most important inputs in Seismic Hazard Analysis (SHA) to estimate the ground motions at both surface and bedrock levels. Region-specific GMPEs are generally derived using the recorded strong motion data available for that region. A serious lack of recorded strong motion data in India has largely restrained the number of available region-specific GMPEs. Due to the very limited data, the previously available GMPEs for the Indian subcontinent have either serious distance or magnitude limitations.

Recorded ground motion data along with a set of simulated synthetic data was used by Anbazhagan et al. [7]. The new GMPE was developed based on a well-established regression model for the Himalayan region. A combined dataset of actual and simulated ground motion data, based on the concept of apparent stations at an equal interval of 10 km was generated. One serious limitation of the already limited Indian recorded strong motion data, large gaps in the dataset pertaining to magnitude vs hypocentral distance was addressed by simulating earthquake motions using FINSIM using the apparent stations concept. This helped to fix the gap in the hypocentral distance and could simulate a good distribution of PGA values along a continuous hypocentral range. A combined dataset of 14 earthquake events with 30 recording stations at an interval of 10 km was generated with a total of 420 data with a moment magnitude range of 5.3–8.7 up to a hypocentral distance of 300 km for GMPE development. Using multi-step regression analysis, a decay parameter was estimated and was used to generate a new region-specific GMPE for the area. New regression parameters were then estimated for the well-established GMPE model to obtain the new GMPE with a larger database. The new GMPE was validated using recorded ground motions which were not used in the regression process. Figure 19 presents the comparison of PGA predicted by various GMPEs with the recorded PGA during the 2011 Nepal–India earthquake.

An attempt was made by Ramkrishnan et al. [81] to develop new GMPEs specifically for shallow crustal and deep-seated earthquakes in the North East subduction zone of the Himalayas using recorded time histories from the Shillong array. Linear regression analysis was performed on the compiled dataset of shallow and deep earthquakes separately, to attain a decay parameter, after which a nonlinear regression model was assumed for developing the new attenuation relations. The ability of the newly developed GMPEs to predict actual recorded data was compared with other relations available in the literature, and it was found that the new GMPEs could predict the values very closely and better than the old GMPEs. The availability of a larger dataset made it possible to provide more realistic and reliable statistical parameters for developing the new region-specific attenuation relations.

Drawbacks of using synthetic ground motions in the development of GMPEs were identified in later studies and new GMPEs for the North and Central Himalayas was presented by Ramkrishnan et al. [83]. A total of 33 earthquakes and 278 recorded time histories were used in the analysis. The GMPE was generated using a similar methodology as the previous study, using multiple regression, considering ground acceleration, magnitude, and hypocentral distance, but using an updated larger dataset consisting of purely recorded acceleration time history. The new GMPE for North and Central Himalayas was applicable to a larger magnitude range of 4.1 to 7.8, and distance range up to 1560kms, thus overcoming a major limitation of currently available region-specific GMPEs. Equation 1 shows the GMPE developed for the North Himalayan region.

$$\log Y = -2.135 + 0.437M - 1.099 \log\left(X + e^{-0.080M}\right) \pm 0.549 \qquad (1)$$

M represents the magnitude of the event and X represents the hypocentral distance. The new GMPE was validated and observed to predict ground acceleration more accurately with noticeably less residuals as compared to existing GMPEs. Figure 20 shows the new GMPE as compared to previously used GMPEs for the region and its potential in predicting ground motion at larger distances. The new GMPE was also compared with recorded PGA from events at shorter hypocentral distances and was found to more accurately predict the ground motion when compared to previous GMPEs.

Considering the more complex tectonic setting of the North East Himalayas, a different GMPE was developed for the region by Ramkrishnan et al. [84] using the same methodology as mentioned above. A total of 24 earthquake events having a total recorded ground motion set of 204 time histories, ranging from moment magnitude of 4.2 to 6.9 and hypocentral distance 42 km to 640 km was used for the work. The new GMPE is presented is shown in Eq. 2.

$$\log Y = -2.607 + 0.580M - 1.004 \log\left(X + e^{-1.332M}\right. \pm 0.477 \qquad (2)$$

The new GMPE was validated by checking its ability to accurately predict the actual recorded PGA of three events which were not considered in the development of the GMPE. Figure 21 shows a comparison of previous GMPEs

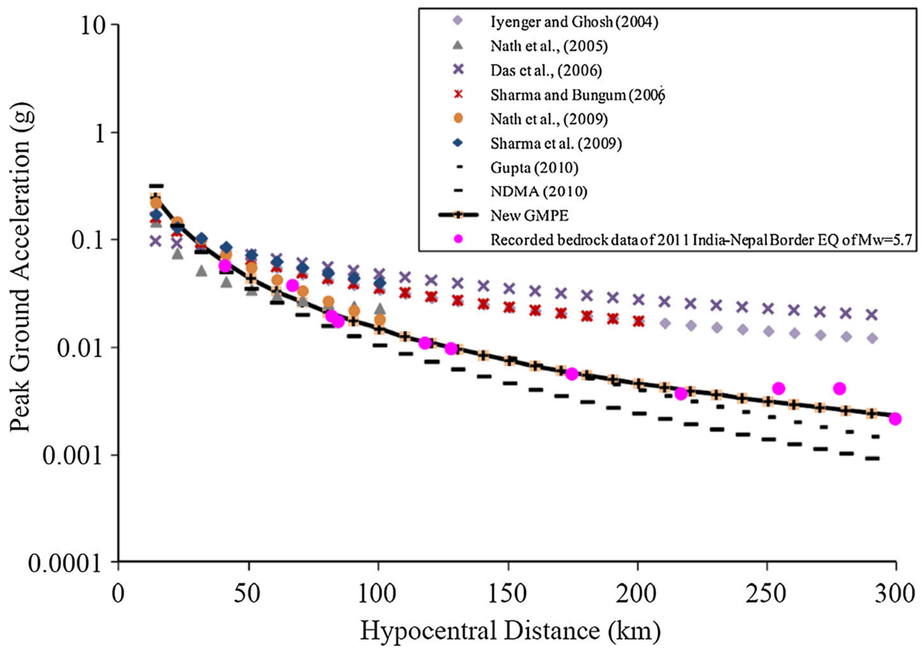


Fig. 19 Comparison of PGA predicted by various GMPEs with the recorded PGA during the 2011 Nepal–India earthquake [7]

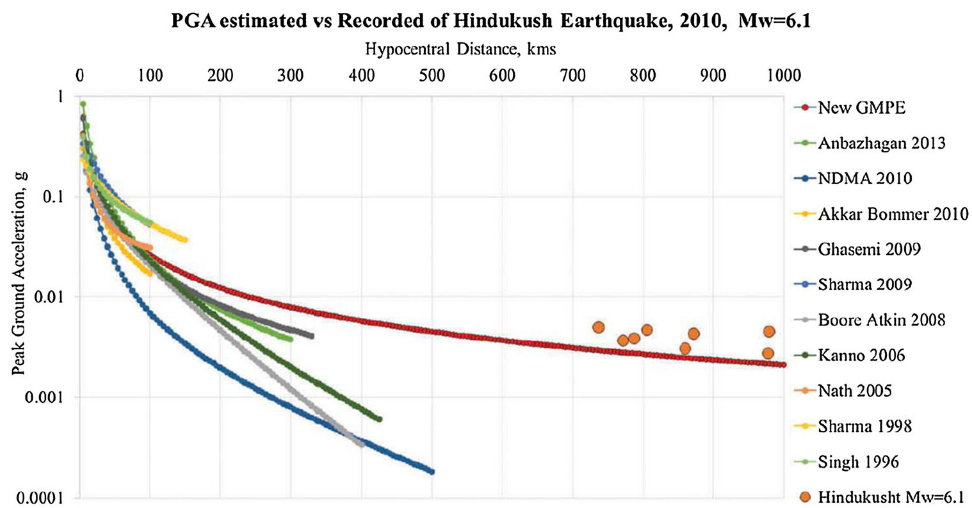


Fig. 20 Comparison of previous and new GMPEs in predicting the actual recorded PGA of the Hindukush earthquake of 2010 [83]

and the new GMPE in predicting the actual recorded ground motion of the India-Burma border earthquake of 1987. The residuals of the actual vs predicted PGAs were plotted and it was found that the new GMPE could predict the GMPEs with much lesser residuals than the previously used region-specific GMPEs.

The most important input in any SHA is the GMPE used. Region-specific GMPEs for the country's most seismically active region, the Himalayas, have been developed considering actual recorded and synthetic ground motions using nonlinear regression analyses. The newly developed GMPEs were validated using data from actual recordings and were found to predict the ground motion more accurately than the existing regional GMPEs and GMPEs that had been adopted for the regions in past studies. The new GMPEs were then used for hazard assessment of the Himalayan region and major cities in the Himalayan region in further studies.

Site Response and Characterization Studies

For a comprehensive site response assessment and microzonation, subsurface characterization considering subsurface profiling is unavoidable. An understanding of the site soil behaviour and response to seismic loading is necessary to assess and mitigate the hazards due to earthquakes. Evaluation of aftermaths of earthquakes has shown that the intensity of ground motion is directly related to soil stratification and type [117, 120]. Constructions supported on

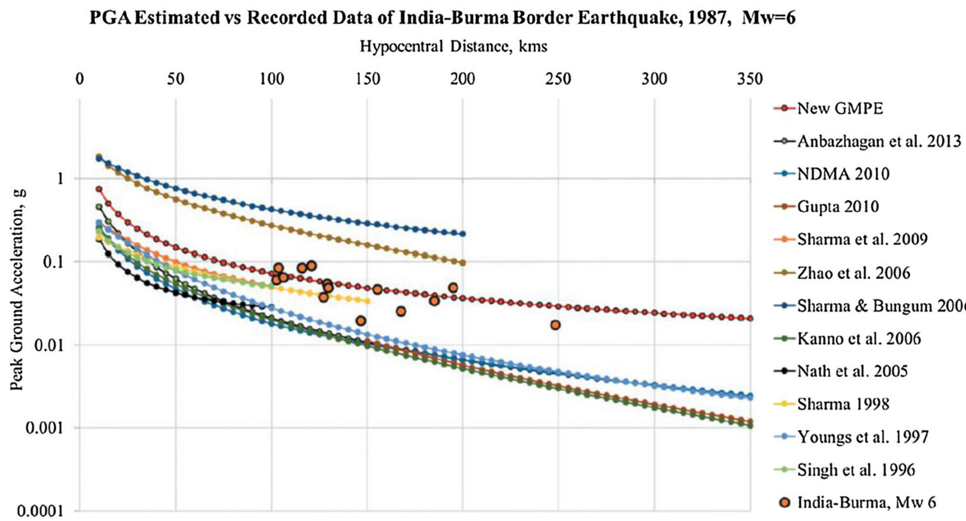


Fig. 21 Comparison of previous and new GMPEs in predicting the actual recorded PGA of the India-Burma border earthquake of 1987 [84]

firm soil and rock perform well when compared to those resting on soft and alluvial grounds. It was observed in the past that, for the same bedrock level input acceleration, the soft soil deposits suffer larger peak acceleration than the hard ground [123]. Several experiences have shown that the response of soil to ground shaking during an earthquake largely influences the level of damage [101, 110, 126]. However, the assessment of ground response is a commonly encountered problem in geotechnical earthquake engineering. Several attempts have been made by geotechnical engineers to define a reliable and quantitative method for predicting the effect of soils on strong ground motion. For this, an understanding of dynamic response characteristics of soils is necessary. To understand the ground response using a one-dimensional approach, several input parameters like design earthquake, bedrock level, soil profile, and other subsurface geotechnical properties are essential [122].

The ground response and geotechnical aspects of Ahmedabad city in the context of the 2001 Bhuj earthquake were studied by Sitharam and Govindaraju [110]. Major geotechnical issues like soil liquefaction, sand volcanoes, ground cracking, and damages to dams, buildings, and embankments were discussed and summarized. To understand the reason behind the damages to the multi-storeyed structures in Ahmedabad city during the Bhuj earthquake, an actual recorded ground motion was analysed using the platform SHAKE91. Seismic response of a site, of which the geotechnical investigation data was available was assessed using this recorded ground motion assuming the ground as a 1-dimensional layered elastic system. Matching of the seismic wave frequencies with resonant frequencies of structures, along with largescale amplification of shear waves at the sites was reported. Further, liquefaction mapping and microzonation of the region was recommended.

Sudhishkumar et al. [63] developed theoretical dispersion curves and compared the same with experimental MASW test results from a site in south Bangalore. Input parameters for the model development like shear modulus, density, layer thickness, and poisons ratio were obtained from SPT tests conducted at the site. 1D and 2D MASW testing was carried out at the site and the dispersion curve model was observed to match well with the experimental curves. Anbazhagan and Sitharam [9] developed a correlation between the shear wave velocity V_s obtained from MASW tests and the N values obtained from SPT tests at a site. The major drawback of SPT data is that it is time consuming, laborious and the results are discontinuous in depth. To address this, geophysical tests are adopted. In this study, 1D and 2D MASW tests were carried out and the subsoil profiles were generated to assess the dynamic properties of the site. It was observed that the bore log data matched well with the MASW test data. A correlation between the geophysical and corrected SPT test results, $V_s = 50\ N_{60}^{0.41}$ was presented in the study, and the representation of the same is shown in Fig. 22. Using a similar approach, using the data obtained from geotechnical and geophysical tests at a site in Southeast Bangalore city, the relationship between corrected SPT N value and shear modulus, G_{max} was developed by Anbazhagan et al. [4].

Sitharam et al. [101] presented the seismic response of soil samples collected from Bhuj, Ahmedabad, and Assam, along with the ground response analysis for a site in Bangalore. Dynamic behaviour of soils collected from Bhuj, Ahmedabad, and Assam was evaluated and the relationship between pore pressure ratio and cyclic shear strain, CSR, shear strain, and number of cycles for initial liquefaction, shear modulus, and shear strain, and damping ratio and shear strain were presented and interpreted [120]. The local site effect in Bangalore was studied using synthetic ground motion using a SMSIM Fortran program.

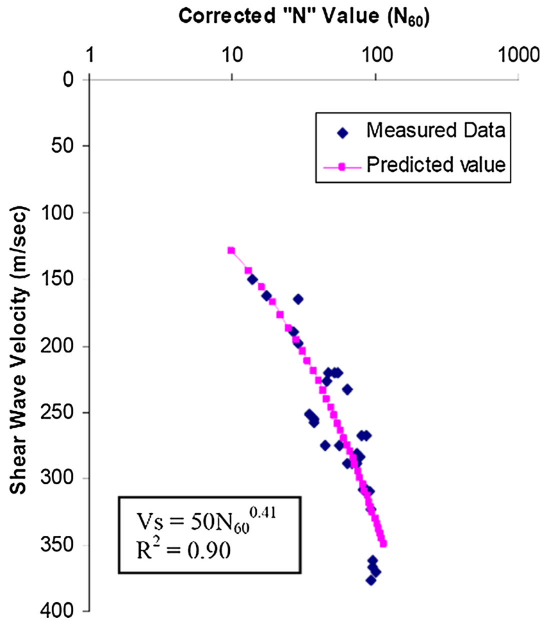


Fig. 22 Correlation between Shear wave velocity and corrected SPT N value [9]

Site-specific ground response analysis was carried out using SHAKE2000 to estimate the amplification factor at 125 different sites in Bangalore, along with the response spectra at the ground surface. The range of amplification factors for the region was found to be 1.022–5.817 and the amplification map of Bangalore is presented in Fig. 23a. It was reported that the amplification factor depends on numerous factors like presence of overburden thickness, frequency of input motion, average shear wave velocity of the soil column and presence of landfills, low SPT values, shallow water table, etc. which contributes to low V_s values [136]. Further, the site characterization of the Bangalore metropolitan area of about 220 km^2 was carried out using a similar method using a refraction survey and shear wave velocity profiling using MASW tests by Anbazhagan and Sitharam [12] and Anbazhagan and Sitharam [13]. A site characterization based on shear wave velocity of 30 m soil profile, V_{s30}, as per NEHRP classification was adopted. 58 1D MASW tests were carried out and based on the results, the major part of Bangalore was classified as site class D and C [12, 13]. Site response was further assessed as discussed above and large modification of wave amplitude at surface level was reported. Combining the data with another 20 2D MASW tests, and estimating the V_{s30}, the whole Bangalore metropolitan area was classified as NEHRP site class D by Anbazhagan and Sitharam [12]. Further, from the 55 locations at which MASW was carried out, SPT data was obtained for generating a correlation between corrected SPT N values and V_s [5]. Figure 23b presents the 30 m average shear wave velocity profile of Bangalore.

Anbazhagan et al. [6] attempted estimation of amplification factors for selected sites in the Himalayan region using isoseismal maps of past events and surface PGA acquired from site response analyses. Ground-level acceleration was estimated from isoseismal maps, as actual ground motion data was not available. Using finite fault simulation (FINSIM), bedrock level ground motions were generated for the events whose isoseismal maps were available and the SPT test data of the sites under scrutiny were collected. Site response analysis was carried out using the synthetic ground motion and subsurface profiles generated from SPT data. The surface-level PGA estimated from the site response analysis using synthetic ground motion and SPT data was then compared with PGA estimated from the isoseismal maps. It was found that the amplification values were matching for both approaches. This methodology could be used as an alternative to understanding site response and estimate site amplification. It further showed that isoseismal maps can be reliably used for the same application.

Anbazhagan et al. [8] carried out seismic site classification studies for Lucknow city and brought out the first correlation between SPT N value and Shear wave velocity, V_s for the Indo Gangetic Basin (IGB). 47 MASW tests were carried out along with 23 boreholes, dug up to depths of 30 m, and subsurface profiling was completed. Further, soil profiles deeper than 150 m were also collected from other sources. The V_s estimated from MASW tests and the SPT N values from the region were found to be comparable and were used to evaluate the 30 m average N value and V_{s30} for site classification as per NEHRP. It was found that the site is classified as C and D based on V_{s30} and D and E based on N_{30}. The suitability of the NEHRP classification for the study region was questioned due to this mismatch. A correlation between V_s and SPT N value specifically for IGB was developed as $V_s = 68.96\ N^{0.51}$ and was compared with existing general correlations available for India. Figure 24 presents the comparison of the new correlation for IGB with existing correlations for India.

Sil et al. [96] and Sil and Sitharam [95] focused on the local site effects of Agartala city in Northeast India. Using the point source model, synthetic ground motion for the whole area was developed considering the uncertainties in the model and input parameters. Using SPT and MASW tests at the site, and interpreting the site response, the site was classified as NEHRP class D. Considering the same, bedrock level acceleration estimated was brought to the ground surface and their amplification factors at 0.2 s and 1 s were reported. Further, the mean design response spectrum at the bedrock and surface levels were developed and compared with that of the Indian standard code driving to the conclusion that the zone factor recommended in IS codes are underestimated. Figure 25a shows the spatial

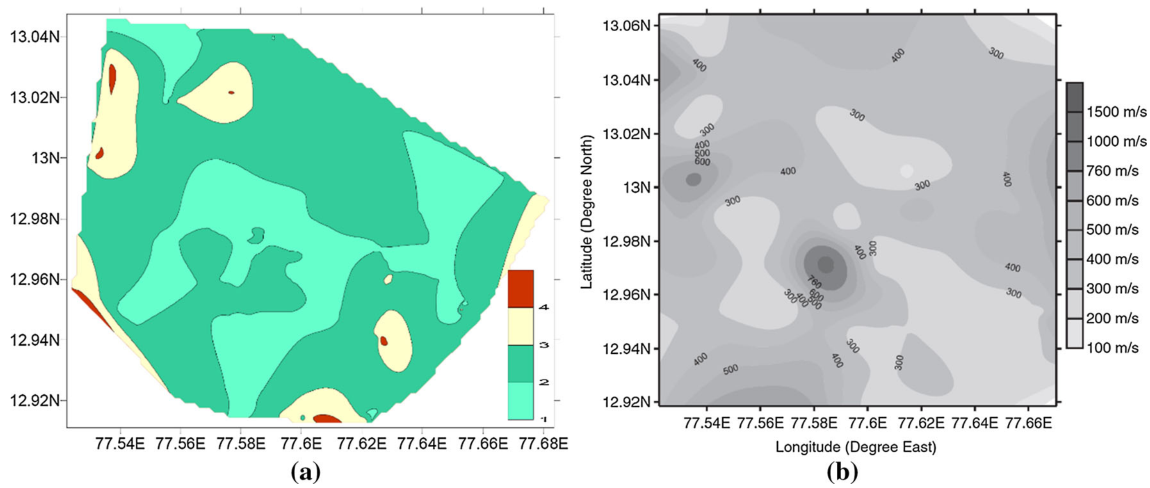


Fig. 23 **a** Amplification Map of Bangalore [101]. **b** 30 m Average shear wave velocity profile of Bangalore [12]

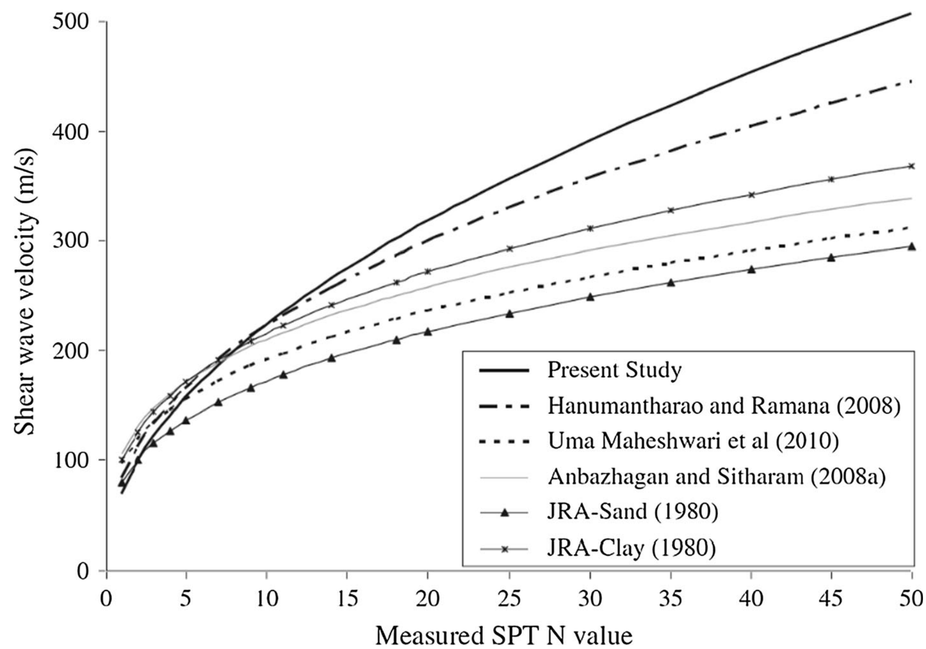


Fig. 24 Comparison of the new V_s—SPT-N correlation for IGB with existing correlations for India [8]

variation of amplification factor for SA at 1 s and (b) shows the comparison of surface-level response spectrum from the current study and recommendation for IS 1893–2002.

Based on a similar approach, Naveen et al. [70] and Naveen et al. [71] carried out field and lab tests to assess the seismic response of the Mavallipura municipal solid waste landfill in Bangalore. Using field and laboratory tests, unit weight, V_s, and shear modulus reduction and material damping ratio relation of the site material was assessed. 1D seismic response analysis using the equivalent linear method was carried out using SHAKE2000 and DEEPSOIL. Low shear stiffness and high amplification were observed at the site, which was associated with the loose filling and damping of the site. Recommendations for a seismically safe landfill design in the Indian scenario was suggested from the studies.

Sitharam et al. [144] carried out a ground response analysis and seismic site characterization of an offshore site in Western Yemen, using a large set of field and laboratory on undisturbed samples. To estimate the low strain soil stiffness and V_s, seismic cone penetration tests (SCPT) were carried out on the field and to estimate dynamic properties like shear modulus and damping ratio, bender element, and cyclic triaxial tests were done. Using synthetic ground motion based on point source models and regional seismotectonic characteristics, equivalent linear ground response analysis was carried out using SHAKE2000 to assess the local site effects. Ground surface-level PGA, its predominant frequency, and

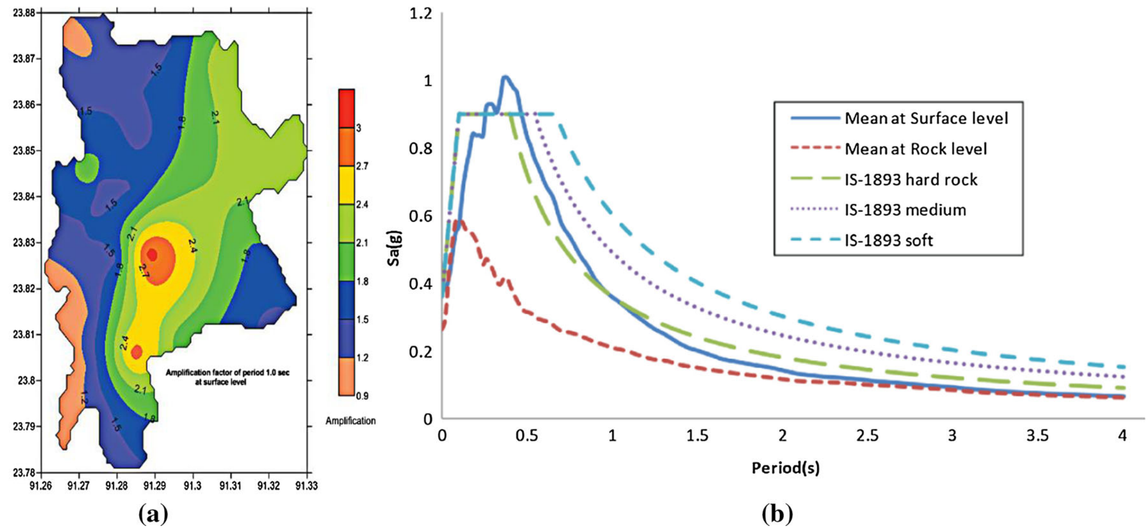


Fig. 25 **a** Shows the spatial variation of amplification factor for SA at 1 s. **b** Comparison of surface-level response spectrum from the current study and recommendation for IS 1893-2002 [96]

amplification factors for the borehole locations were estimated. Based on these results, a ground surface-level design response spectra corresponding to 475 and 2500 years return periods were developed and presented based on Eurocode 8.

Site response studies have been carried out for important regions in the country using field tests comprising of SPT, CPT, MASW, etc. 3D subsurface profiles have been generated and the amplification factors for these sites have been estimated. Extensive field and laboratory tests were carried out to achieve this. Site response and amplification factors are indispensable for estimating the surface-level hazard and other earthquake-related hazards like liquefaction, mudflows, and ground subsidence. Besides, correlations between shear wave velocities and SPT N values have been generated for the Indo Gangetic Basin and Bangalore city.

Liquefaction Studies

Liquefaction is a phenomenon, where the saturated, cohesionless, loose soil loses its shear strength caused by large and sudden pore pressure build-up under earthquake or similar loading. Soil tends to flow like a viscous liquid which causes a significant drop in soil bearing capacity and induces failure due to settlement in the structures. Bridge and building foundation failure and slope failure are very commonly observed during liquefaction. A typical scenario of soil liquefaction in India was witnessed during the 2001 Bhuj earthquake of M_w 7.7. To understand and evaluate liquefaction potential, two parameters need to be calculated—seismic loading and soil response. In this, the primary stride is to assess the seismic loading, which can be done using various methods explained in previous sections. Second, the response of the soil at the site, which can be carried out using field and laboratory tests. The most widely accepted methodology for assessing liquefaction potential was proposed by Seed and Idriss [94], where the factor of safety against liquefaction is dependent on the ratio of cyclic shear strength of soil to the cyclic stress developed in the soil during an event. The appraisal of cyclic shear strength needs laboratory studies like the cyclic triaxial test, cyclic torsional test on undisturbed soil samples. Considering the difficulties in obtaining undisturbed soil samples, evaluation of liquefaction potential from field tests have gained popularity too. Major in situ tests adopted for liquefaction studies are the standard penetration test (SPT), cone penetration test (CPT), Becker penetration test (BPT), and the shear wave velocity test (Vs). Extensive studies on the liquefaction potential of various regions had been carried out by the author using both these methods. Notable studies are discussed in this section.

Anbazhagan et al. [16] assessed the response of overlying soil to evaluate the amplification and liquefaction potential of the city of Bangalore. To assess the site amplification and response, bedrock level PGA estimated in their past studies, SPT data, and other geotechnical information, and synthetically generated ground motion was used for an equivalent linear analysis using SHAKE-2000. After obtaining the amplified ground-level PGA, liquefaction studies were done using the Seed and Idriss [94] approach. It was found that the site had a high liquefaction factor of safety. Cyclic triaxial tests were conducted on undisturbed samples from the sites and the results obtained from Seed and Idriss [94] approach were validated. It was found that this approach is reliable and could be adopted for other borehole data from the site and could be used for microzonation.

Sitharam et al. [129] developed a 1:20,000 scale 3-dimensional subsurface model for the Bangalore city using data from an extensive geotechnical investigation. Using this model, a preliminary liquefaction susceptibility map was generated based on the Seed and Idriss [94] method. Cyclic triaxial tests were carried out on samples collected from the boreholes in the study region to confirm the estimated liquefaction factor of safety. Liquefaction hazard maps for 6 and 7 M_w events were generated from the results and presented. It was found that most parts of Bangalore are safe from liquefaction hazard, except few locations where the overlying soil is sandy silt and the water table is at a shallow depth.

Conventional liquefaction potential estimation approaches do not consider the uncertainty in the estimation of the earthquake ground shaking. Considering this, performance-based probabilistic methods for liquefaction analyses were adopted by Vipin et al. [155], Sitharam and Vipin [109], Vipin and Sitharam [148], Sitharam and Vipin [108] and Vipin et al. [152]. Sitharam and Vipin [109] used this probabilistic liquefaction evaluation method, where the input ground motion was estimated using a comprehensive PSHA for bedrock level ground motion. The bedrock level PGA was brought to surface level using amplification factors based on SPT and V_s from about 500 site investigations, and NEHRP classifications from remote sensing data for the Bangalore urban centre and peninsular India, respectively. From the study, a map of FOS against liquefaction for Bangalore for a return period of 475 years was developed. Further, the spatial distribution of SPT and CPT values necessary to avoid liquefaction for peninsular India, specifically Bangalore urban centre were also presented. Vipin and Sitharam [148] carried out an extensive performance-based liquefaction potential assessment for Bangalore city based on probabilistic ground motion and site response using SPT values from site investigations and V_s from MASW tests. Probability of liquefaction and FOS against liquefaction maps for a return period of 475 and 2500 years, at different soil depths of 3 m and 6 m, were reported. Further, SPT values required for the prevention of liquefaction for the mentioned return periods and soil depths were also reported. Vipin et al. [152] later compared these findings to the FOS against liquefaction using deterministic approaches [129] and found that the latter was slightly higher. They concluded that about 35% and 60% of the Bangalore region have a FOS against liquefaction greater than 2 at depths of 3 m and 6 m, respectively. Figure 26a presents the FOS against liquefaction at 3 m soil depth for a return period of 475 years. Later, using NEHRP classifications for site response, similar work was carried out for the whole of south India by Sitharam and Vipin (2010). The corrected SPT values required to prevent liquefaction for POE of 2% and 10% in 50 years were reported as shown in Fig. 26b.

Vipin et al. [151] and James et al. [49] carried out a similar performance-based liquefaction potential assessment for the states of Gujarat and Karnataka, respectively. PSHA was carried out for both the regions using three different GMPEs and bedrock level ground acceleration was estimated. Considering the vastness of the study regions and the absence of extensive subsurface models or geotechnical data, the site characterization for site response was carried out based on the NEHRP schemes. Both the states were assumed to fall under site class D, as soils in other site classes are stiffer and may not liquefy. Considering appropriate amplification factors recommended by Raghukanth and Iyengar [159], the bedrock level PGA was brought to the ground surface for further analyses. The liquefaction potential was estimated and reported based on the corrected SPT value essential to avoid liquefaction. The spatial variation of corrected SPT values required for both the states to avoid liquefaction for return periods of 475 and 2500 years was mapped. Figure 27a presents the required corrected N values at 3 m depth for liquefaction prevention for the states of Gujarat and (b) Karnataka. For the state of Karnataka, the results were further supplemented with CPT values at 3 m depth for liquefaction prevention for return periods of 475 and 2500 years.

Vipin and Sitharam [154] and Vipin et al. [153] attempted incorporating the logic tree framework into the assessment of liquefaction potential to reduce the epistemic uncertainties. The water table was assumed to be on the ground surface to consider the worst-case scenario condition. Site response was evaluated based on six different NEHRP classifications, using the amplification factors provided by Raghukanth and Iyengar [159]. Using these, the liquefaction hazard curves with respect to corrected SPT and CPT values for peninsular India were generated. The spatial variation of corrected SPT N values and CPT values at 3 m depth required to avoid liquefaction for 2% and 10% POE in 50 years were reported in the study. Using a more extensive logic tree approach, using areal and linear sources, two approaches for maximum magnitude estimation, and three GMPEs, a probabilistic approach for liquefaction potential estimation was attempted again for the state of Gujarat. It was observed that the Rann of Kutchh region of Gujarat has high liquefaction potential which was validated in the 2001 Bhuj earthquake.

So far, the studies were based on the liquefaction susceptibility, or FOS against liquefaction, or, the SPT and CPT values required to avoid liquefaction for soils at specified depths. Iwasaki et al. [43] introduced the

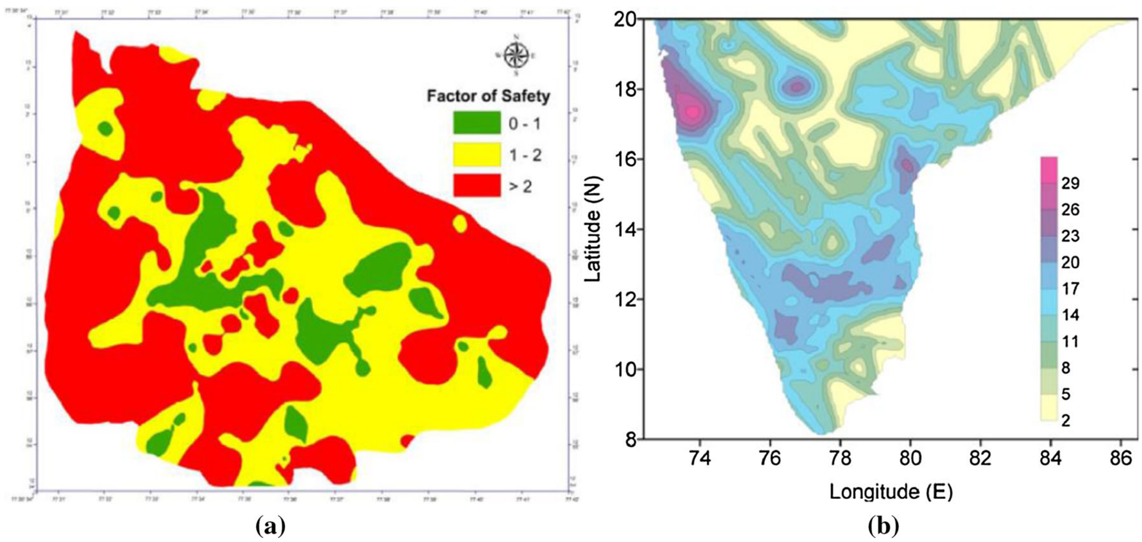


Fig. 26 **a** FOS against liquefaction at 3 m soil depth for a return period of 475 years in Bangalore Urban Centre [152]. **b** SPT N values required at 3 m soil depth to avoid liquefaction for a return period of 2500 years in Peninsular India [108]

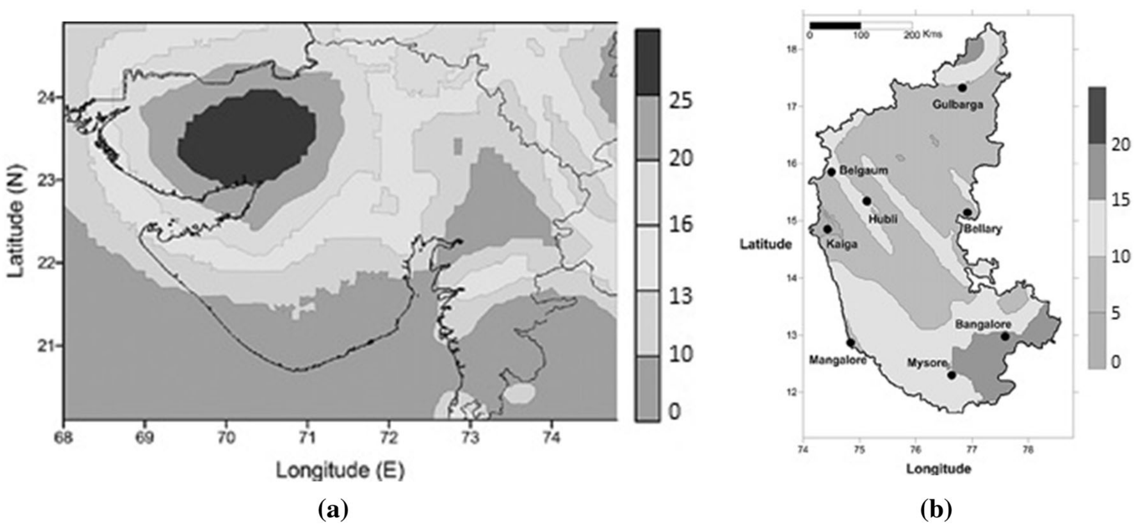


Fig. 27 Corrected N values at 3 m depth for liquefaction prevention for the states of **a** Gujarat [151] and **b** Karnataka [49]

Liquefaction Potential Index (LPI) which is obtained by integrating the FOS against liquefaction at all depths and is a better representative of the liquefaction potential at a particular borehole location. James et al. [50] adopted this method and carried out a deterministic and probabilistic approach to estimate the LPI at a nuclear power plant site located in the South Indian east coast, using field test data. LPI provides a number and its range represents the liquefaction vulnerability of the site. A value of less than 2 means low vulnerability and above 15 is very high vulnerability [139]. Seismic loading was estimated using deterministic and probabilistic methods considering three GMPEs and linear source models by dividing the site into grids of size 0.001° × 0.001°. Based on extensive field testing using MASW and SPT tests, the site classes were classified ranging from C to E as per NEHRP. Using the relations from Raghukanth and Iyengar [159], the bedrock level PGA was brought to surface level to estimate the Cyclic Stress Ratio (CSR), and the SPT test data was used to estimate the Cyclic Resistance Ratio (CRR). Based on these values, the FOS against liquefaction was estimated, using which the LPI was estimated. Deterministic assessment of LPI and probabilistic LPI for return periods of 475 and 2500 years were reported. Figure 28a shows the spatial variation of LPI of the site, for a 2500 years return period. A similar approach was adopted for the LPI mapping of Lucknow city, a part of the Indo Gangetic Basin (IGB), lying in the foothills of the highly seismic Himalayas by Kumar et al. [61]. Field tests using MASW and SPT were carried out and a deterministic approach was adopted for estimating PGA in this study. LPI and FOS against liquefaction considering average and maximum surface PGA amplification was reported in the study. Figure 28b presents the spatial variation of LPI considering maximum site amplification for Lucknow city.

Kolathayar et al. [57] carried out a comprehensive probabilistic liquefaction potential assessment for India and adjoining areas using a logic tree approach. Assuming the worst-case scenario, the water table was assumed to be at the ground level and the whole region in NEHRP site class D. Spatial variation of corrected N values required to avoid liquefaction with 2% and 10% POE in 50 years was reported in this study. Figure 29 presents the spatial variation of corrected N values required for a return period of 2475 years.

Extensive studies on site amplification had been carried out by the author and based on the same, liquefaction studies have been extended for those regions. SPT N values required at various depths to avoid liquefaction for Bangalore, Kalpakam, Gujarat, Karnataka, South India, and the whole country had been reported in various studies. Extensive field studies were carried out for estimating the site amplification for the cities of Lucknow, Bangalore, and Kalpakam, and proxy methods were adopted for large scale studies like that of South India and the whole country. LPI and FOS against liquefaction were reported in these studies, based on which further microzonation and risk mapping could be carried out as discussed in the following sections.

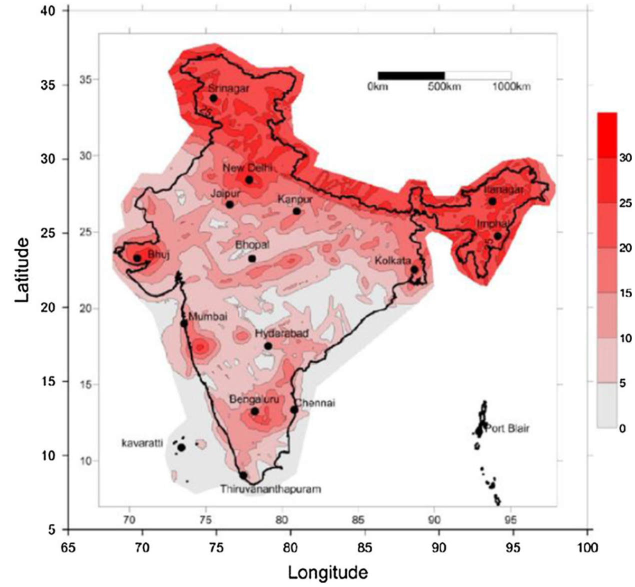


Fig. 29 Spatial variation of corrected N values required for a return period of 2475 years [57]

Seismic Microzonation and Applications of GIS

Seismic Zonation is the practice of subdividing a region into different categories or zones based on various geotechnical, geological, and seismological parameters for effective use in land-use planning for earthquake effects [99]. It is generally carried out at the micro-level, meso-level, and macro-level [47]. James and Sitharam [47] recommended the aptness of different levels of seismic

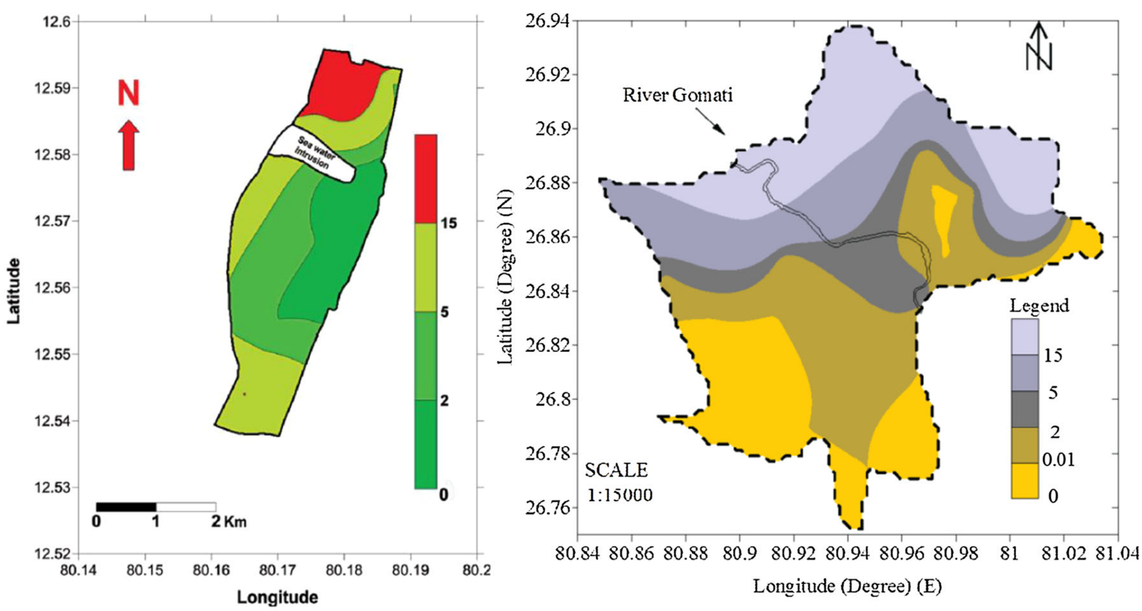


Fig. 28 **a** Spatial variation of LPI for a 2500 years return period [50]. **b** Spatial variation of LPI considering maximum site amplification for Lucknow city [61]

zonation for different regions and methodologies for seismic site characterization, amplification hazard, and liquefaction hazard. The detailed description presented by James and Sitharam [47] is presented in Table 5.

Sitharam and Anbazhagan [137] defined microzonation as follows:

> The microzonation is defined as subdivision of a region into zones that have relatively similar exposure to various earthquake related effects. This exercise is similar to the macro level hazard evaluation but requires more rigorous input about the site specific geological conditions, geotechnical characteristics of site, ground responses of soil column to earthquake motions and their effects, ground conditions which would enhance the earthquake effects like the liquefaction of soil, the ground water conditions and the static and dynamic characteristics of foundations or of stability of slopes in the hilly terrain

A general idea of structures that are suited to an area, relative damage potential of existing structures, or potential hazard or threat to a region can be obtained from microzonation maps [98]. Damages due to earthquakes are dependent on three basic factors, source and path characteristics of the earthquake, local site effects, and design and construction features of the structure. A seismic microzonation should address numerous parameters in the first two basic groups. Basic microzonation assesses the site response based on its characterization, and works as a first step in seismic risk mitigation [137]. For seismic risk mitigation practices, seismic hazard maps developed based on geotechnical data are widely being incorporated. Remote sensing data are extensively used for finding linear sources and mapping point sources, which is a major input in seismic hazard assessment. Mapping and delineating earthquake sources have been made easy with the use of remote sensing data and can be stored for future use in similar studies using Geographical Information Systems (GIS) and applications. GIS also offers a concrete platform for incorporating diverse layers of information, thereby providing valuable input for earthquake-resistant design of structures and town planning [10, 133]. Land-use dynamics, site geology, liquefaction susceptibility, urban region mapping, etc.,, can be incorporated in multi-criteria-based microzonation studies using remote sensing data processed in various GIS platforms.

Sitharam et al. [121] attempted a first level microzonation mapping of the Bangalore region considering parameters like peak ground acceleration and amplification factors to generate a FOS against liquefaction map of Bangalore city. Hazard analysis was carried out and based on geotechnical and remote sensing data [136]. Amplification factors were estimated for the study region and 2D hazard maps for these were developed using the ArcInfo package-based GIS tool. The region was divided into three zones of amplification; A to C ranging from no to moderate amplification and merging it with the PGA map, a FOS against liquefaction map was presented which classified the area into 5 zones of liquefaction susceptibility.

Anbazhagan and Sitharam [3], Sitharam and Anbazhagan [137], and Sitharam and Anbazhagan [111] improved this study and presented a 1:20,000 scale FOS against liquefaction map of Bangalore city based on various geotechnical, geological and seismological parameters. Detailed methodology and results of Deterministic bedrock level ground motion, site amplification factor, Soil thickness from geotechnical SPT tests, Equivalent V_s based on MASW tests, Predominant period, and frequency, Geology and geomorphology of the site were developed and presented using a GIS platform. Using the above data, a basic

Table 5 Approaches and grid size recommended for micro-, meso- and macro-levels of seismic zonation [47]

Earthquake hazard	Methodologies (grid size)		
	Micro-level	Meso-level	Macro-level
Seismic Hazard at bedrock level	Deterministic/Probabilistic approach (less than 1 km × 1 km)	Deterministic/Probabilistic approach (1 km × 1 km to 5 km × 5 km)	Deterministic/Probabilistic approach (5 km × 5 km to 10 km × 10 km)
Seismic Site Characterization	Geotechnical and Geophysical Testing (less than 1 km × 1 km)	Geotechnical and Geophysical Testing/ Topographic slope map (1 km × 1 km to 5 km × 5 km)	Topographic slope map (5 km × 5 km to 10 km × 10 km)
Site Amplification Hazard	Ground Response Analysis (less than 1 km × 1 km)	Ground Response Analysis/Empirical Method (1 km × 1 km to 5 km × 5 km)	Topographic slope map (5 km × 5 km to 10 km × 10 km)
Liquefaction Hazard	Deterministic/Probabilistic method based on field test data (less than 1 km × 1 km)	Deterministic/Probabilistic method based on field test data (1 km × 1 km to 5 km × 5 km)	Performance-Based Approach (5 km × 5 km to 10 km × 10 km)

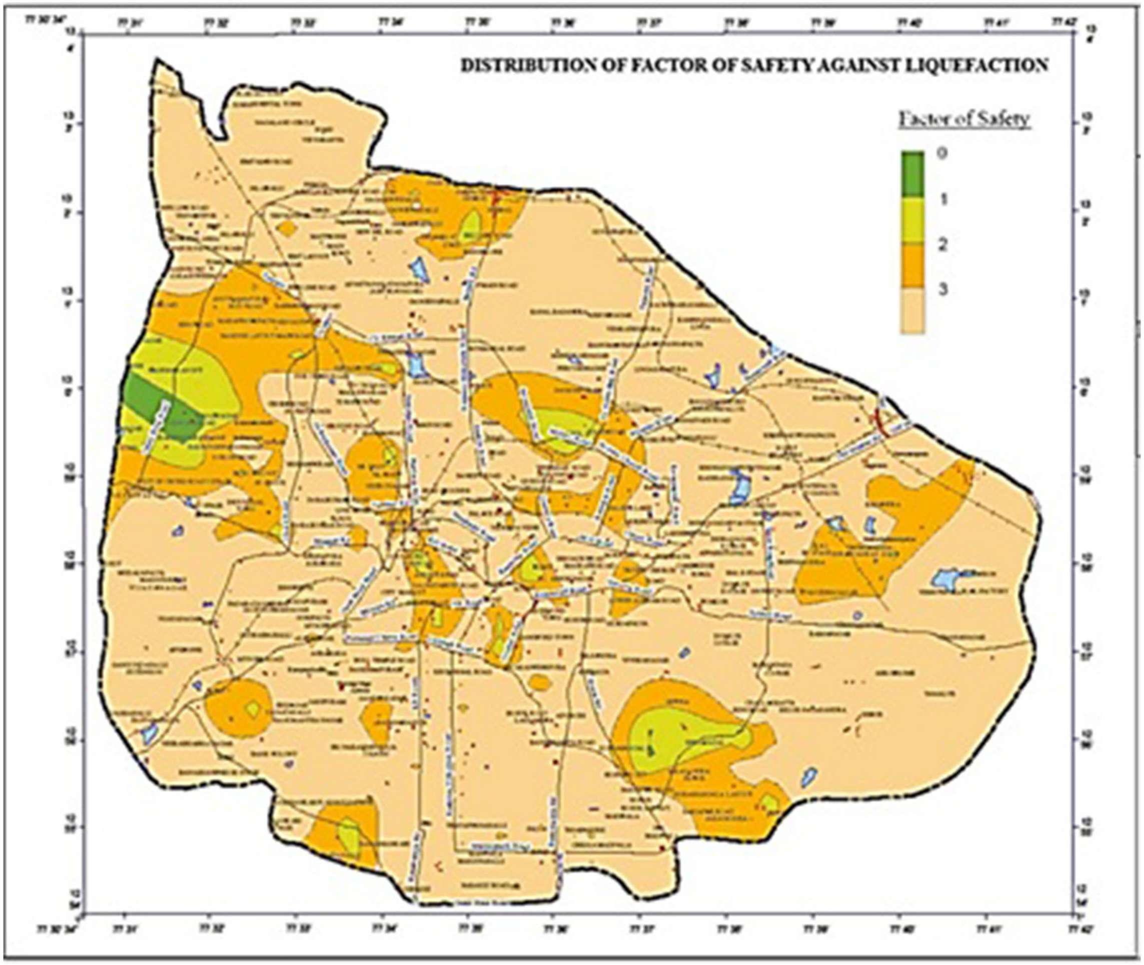


Fig. 30 Basic microzonation map of Bangalore city showing FOS against liquefaction [137]

FOS against liquefaction map was developed and presented, which divided the whole region into 4 levels of liquefaction hazard as shown in Fig. 30.

Detailed discussions on the principles, practices, and review of microzonation studies in India were presented by Sitharam and Anbazhagan [137] and Sitharam et al. [132]. Past microzonation studies of Indian cities like Jabalpur [75], Dehradun [77], Delhi [23], Sikkim [68], and Guwahati [68] were discussed and a recommendation was made to incorporate geotechnical aspects and assign them apt weightages for microzonation [113]. Considering this, a detailed microzonation of Bangalore city was attempted by Sitharam and Anbazhagan [137] and Anbazhagan et al. [14]. Numerous criteria were selected for microzonation of Bangalore and weights were incorporated to them based on their importance. In the order of weights assigned, the parameters considered were bedrock level PGA using DSHA, bedrock level PGA using PSHA, site amplification factor, soil thickness from geotechnical SPT tests, equivalent V_s based on MASW tests, factor of safety against liquefaction, predominant period/frequency, ground elevation levels or topography, drainage pattern, and geology and geomorphology of the site. These parameters were merged using an Analytical Hierarchy Process (AHP) which incorporated a ranking of the themes considered using a pair-wise comparison matrix of themes and their normalized weights. The parameters discussed above, based on their weights were merged to develop hazard index-based deterministic and probabilistic microzonation maps. The probabilistic seismic microzonation map for the city of Bangalore presented in this work is shown in Fig. 31.

Sitharam et al. [100] and James et al. [48] carried out a comprehensive seismic microzonation of Lucknow city and a nuclear power plant site based on a similar methodology. For the study regions, a region-specific GMPE and two GMPEs developed for other regions were used in a logic tree framework to carry out DSHA and PSHA to estimate the bedrock level PGA. 2D lithological cross-sections of the study area were developed using 23 boreholes and 47 MASW tests. The amplification factor for the region was estimated based on this geotechnical and

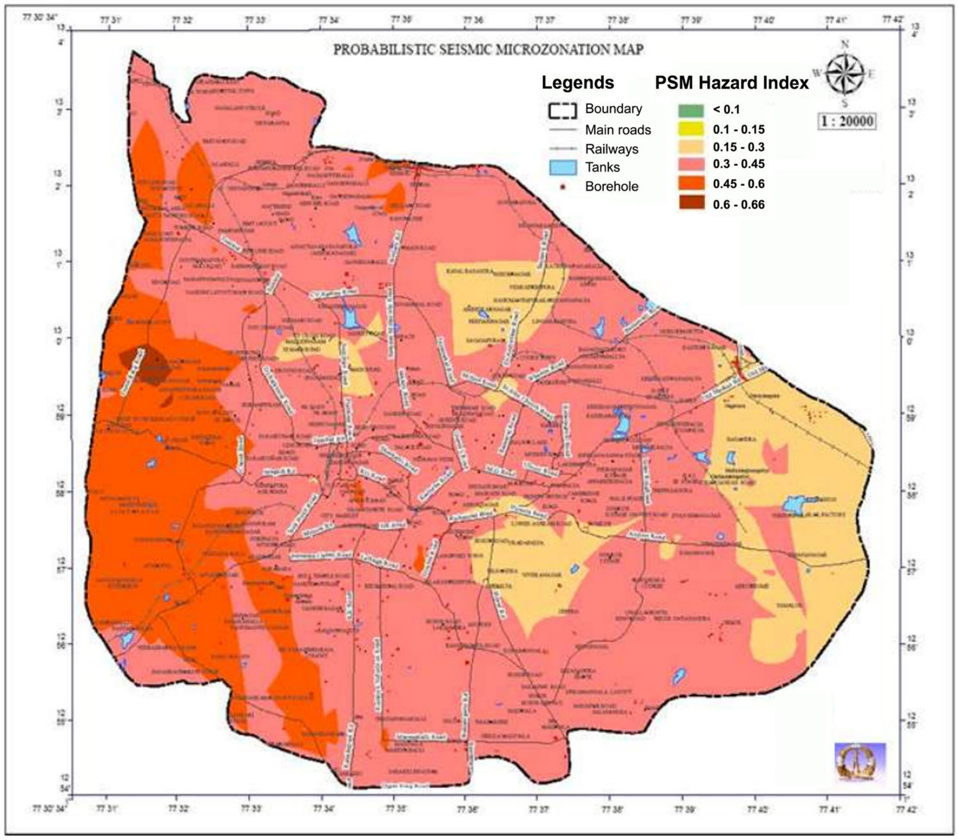


Fig. 31 Probabilistic Seismic Microzonation map of Bangalore city [137]

geophysical survey and the surface PGA was mapped and used for assessing the FOS against liquefaction. Using an AHP, using weighted factors like rock level PHA from DSHA, rock level PGA from PSHA with 2% and 10% POE in 50 years, amplification factor, V_{s30}, average V_s till a depth where shear wave velocity if reaching 760 ± 60 m/s, FOS against liquefaction, and predominant frequency, a seismic hazard index was estimated for the study region. Deterministic and probabilistic microzonation maps of Lucknow were then developed based on the seismic hazard index. Figure 32a presents the probabilistic seismic microzonation map of Lucknow for 10% POE in 50 years. Using parameters like PHA from DSHA and PSHA, amplification factor, FOS against liquefaction, predominant frequency, V_{s30} and overburden soil thickness, deterministic, and probabilistic hazard index were defined for the nuclear power plant site. Figure 32b presents the probabilistic seismic microzonation map of the power plant site for 10% POE in 50 years.

Application of GIS in seismic studies was explored further by James and Sitharam [45] in assessing the Macro-level landslide hazard for the state of Karnataka, India. A macro-level hazard assessment was carried out to identify seismic landslide hazard-prone regions using Digital Elevation Model (DEM) data. The DEM was processed to develop a slope map of the state. After dividing the whole region into grids of size 50 m × 50 m, the bedrock level hazard was estimated using the DSHA approach for those grid points having terrain slope above 10°. Surface-level PGA was estimated using the nonlinear site amplification technique considering NEHRP site class B. Considering the two parameters—surface-level PGA and terrain slope angle, the seismic landslide hazard for each grid point was reported in terms of static FOS using Newmark's analysis. The district-wise analysis was carried out and later merged to obtain the seismic landslide hazard map of the whole state. The state was delineated into three categories based on static FOS, Low, moderate ad high hazard regions, with FOS 1–1.5, 1.5–2, and above 2, respectively. Figure 33a) shows the seismic landslide hazard map of the state of Karnataka. A similar approach and classifications were adopted by James and Sitharam [46] for studying the state of Sikkim and delineating it into different zones of seismic landslide hazard as shown in Fig. 33b. It was observed that the majority of the terrain of the state of Karnataka was flat terrain and had low hazard, whereas the western ghat region had a very high hazard. For the state of Sikkim, it was observed that the majority of the state fell under high hazard, which was predominantly due to the high level of predicted ground shaking in the range of 0.2–0.3 g, and the extremely steep terrain.

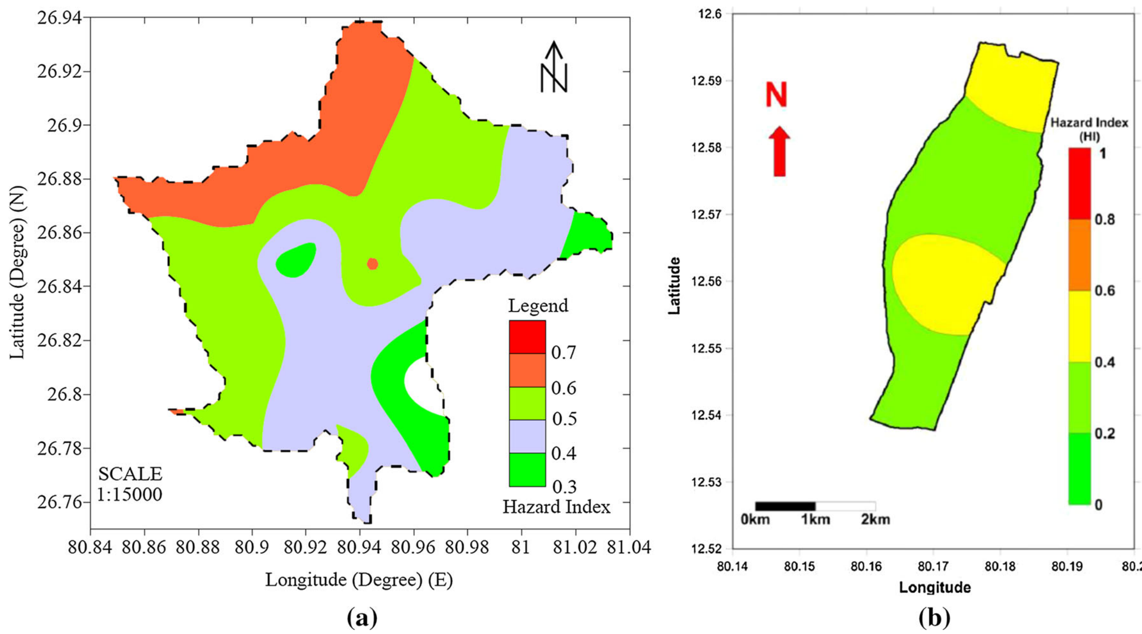


Fig. 32 Probabilistic seismic microzonation map for 10% POE in 50 years, **a** Lucknow [100], **b** Nuclear power plant site at Kalpakam [48]

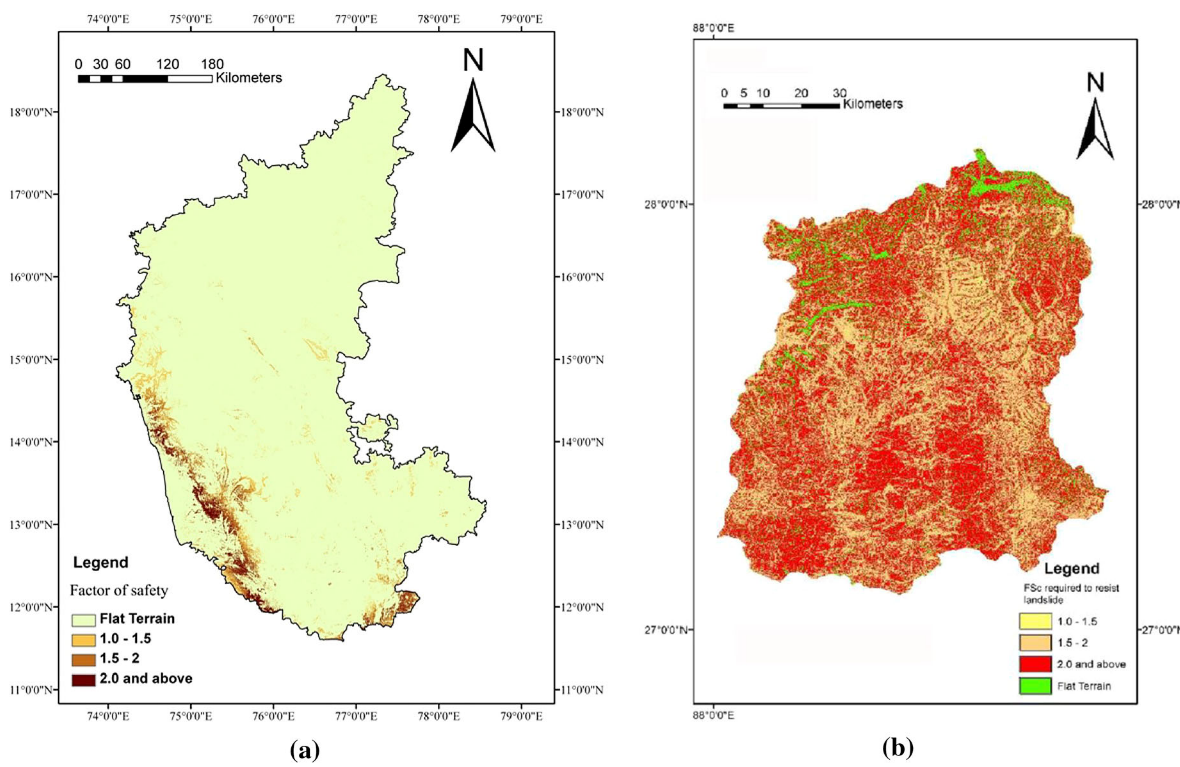


Fig. 33 Seismic landslide hazard map of the state of **a** Karnataka [45]. **b** Sikkim [46]

Seismic microzonation based on deterministic and probabilistic approaches were carried out for various regions on various scales. Microzonation of cities like Bangalore, Lucknow, and Kalpakam were carried out considering their liquefaction susceptibility and seismic slope stability. Various other contributing parameters like amplification factor, bedrock level PGA, predominant frequency, shear wave velocity, etc. were considered and merged to establish a hazard index for the region in many studies. Microzonation maps of Bangalore, Lucknow, and

Kalpakam were thus generated in terms of deterministic and probabilistic hazard indices. Using a similar approach, microzonation and hazard maps in terms of FOS against seismic landslide susceptibility were reported for the states of Karnataka and Sikkim.

Time–Frequency Analysis in Seismic Studies

Earthquake signals recorded by accelerograms exhibit non-stationary characteristics and demonstrates a time-evolving frequency structure. The transient earthquake signals are non-stationary in the context that the amplitude of the frequency varies over time. The non-stationary features of earthquakes are linked to the period of ground motion intensity and the frequency content time variation. Time–Frequency distributions transform a one-dimensional signal into a two-dimensional time and frequency function and define how the signal's spectral content changes over time. Besides, the time–frequency distribution demonstrates how the signal energy is distributed simultaneously over time and frequency domain. Time–Frequency Analysis (TFA) is therefore implemented to better analyse the spectrum and detect the seismic signal. Fourier analysis has been used for decades for representing the frequency plane in seismic signals. The Fourier spectrum provides the contents of frequency in time series; nevertheless, the identification of the temporal location of identical frequency, as well as, the change of frequencies in time is not defined in the spectrum aforementioned. Point source models were used in stochastic seismological models for ground motions synthesis in several past studies. The duration, frequency contents, and amplitudes of ground movement at a location are controlled by the directivity and rupture propagation effects. But the point source models were unable to capture these effects effectively. Further, Fourier Transform (FT) had been used in past studies in an attempt to synthesize ground motions [60], but it was observed that the temporal distribution of frequency contents over the time–frequency plane was not similar to that of the actual signals. Hence, control over time–frequency content was recommended while synthesizing signals, especially for usage in nonlinear analyses. Time–Frequency distributions map a one-dimensional signal into a two-dimensional function of time and frequency and describe how the spectral content of the signal changes with time, and are also termed as Joint-Time–Frequency Analysis/Representations (JTFA/JTFR). The time-domain function demonstrates how signal amplitude changes with time while the frequency domain demonstrates the pattern of such modifications. Furthermore, Time–Frequency distribution shows how the energy of the signal is distributed over time and frequency domain simultaneously. TFA techniques have been adopted by Ramkrishnan [78] to analyse and synthesize ground motion for nonlinear analyses.

Ramkrishnan et al. [79] adopted the Gabor Transform (GT), a Joint Time–Frequency Analysis (JTFA) technique to synthesize earthquake motions for the Japanese region. Recorded time-histories of 23 earthquakes throughout Japan was been collected from K-Net and Kik-Net Strong Motion Seismograph Network and was categorized according to various Magnitude and hypocentral distances [80]. Events of magnitude ranging from 5 to 5.5 and hypocentral distances 0 to 100 km were sorted and GT was applied to transform the signals to their time–frequency domain and estimate their Gabor amplitude coefficients. Mean Gabor amplitude coefficients were estimated for different Magnitude (M_x) and Distance (D_y) combinations like M_5D_{0-25}, M_5D_{25-50}, $M_{5-5.5}D_{0-25}$, and $M_{5-5.5}D_{25-50}$. Using an inverse GT process; Gabor Expansion (GE), the mean transformed Gabor amplitude coefficients were used to reconstruct and synthesize a time-history which does not compromise on the quality of their spectral and frequency contents, thus yielding reliable synthetic seismic motions. Response spectra are developed from the actual and synthesized time-histories and are compared. A statistically good fit in terms of the coefficient of determination factor, R^2 was observed between the actual and synthetic response spectrum developed. The GT spectrogram and physiogram of a sample synthetic seismogram developed for an event of magnitude 5 and a distance range of 0–25 km from the epicentre are presented in Fig. 34. Using a similar approach, Ramkrishnan et al. [79] developed synthetic signals for the Japanese region for magnitudes ranging from 5.5 to 6.0 and hypocentral distances ranging from 0 to 50 km.

Ramkrishnan et al. [82] and Devaraj et al. [34] adopted a Joint Time–Frequency Analysis (JTFA) technique for the synthesis of accelerograms for the North and Central Himalayas and North East Himalayas, respectively. JTFA was adopted for analysing the signals in a joint time and frequency domain to better understand its characteristics and synthesize signals without compromising its inherent characteristics like frequency content and amplitude. Synthetic accelerograms were developed using JTFA techniques for different magnitude and distance ranges between 5 to 6.8 and 0–480 km and the corresponding generalized response spectra were developed by Devaraj et al. [34]. Synthetic accelerograms and their response spectra were compared with actual signals in the same magnitude-distance ranges and were found to match well. A comparison of the frequency contents of actual and synthetic signals was also carried out using FT and GT spectrograms and was found to be in good agreement. Further, a comparative study of various earthquake reduction measures for NEI was carried out for a scenario earthquake using the

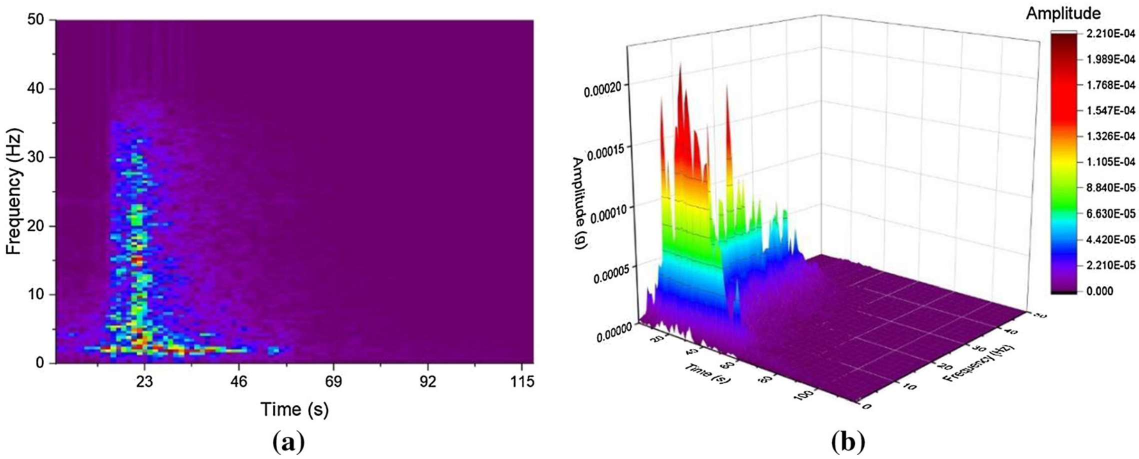


Fig. 34 **a** GT spectrogram and **b** Physiogram of a sample synthetic seismogram developed for an event of magnitude 5 and distance range of 0–25 km for Japan region [79]

synthesized data, and the best suitable structural input for the region was recommended from the nonlinear analysis. Figure 35 presents the frequency content comparison between actual and synthetic ground motions developed for the North East Indian region, for a magnitude and distance range of 5.5–6 and 201–240 km, respectively. It could be

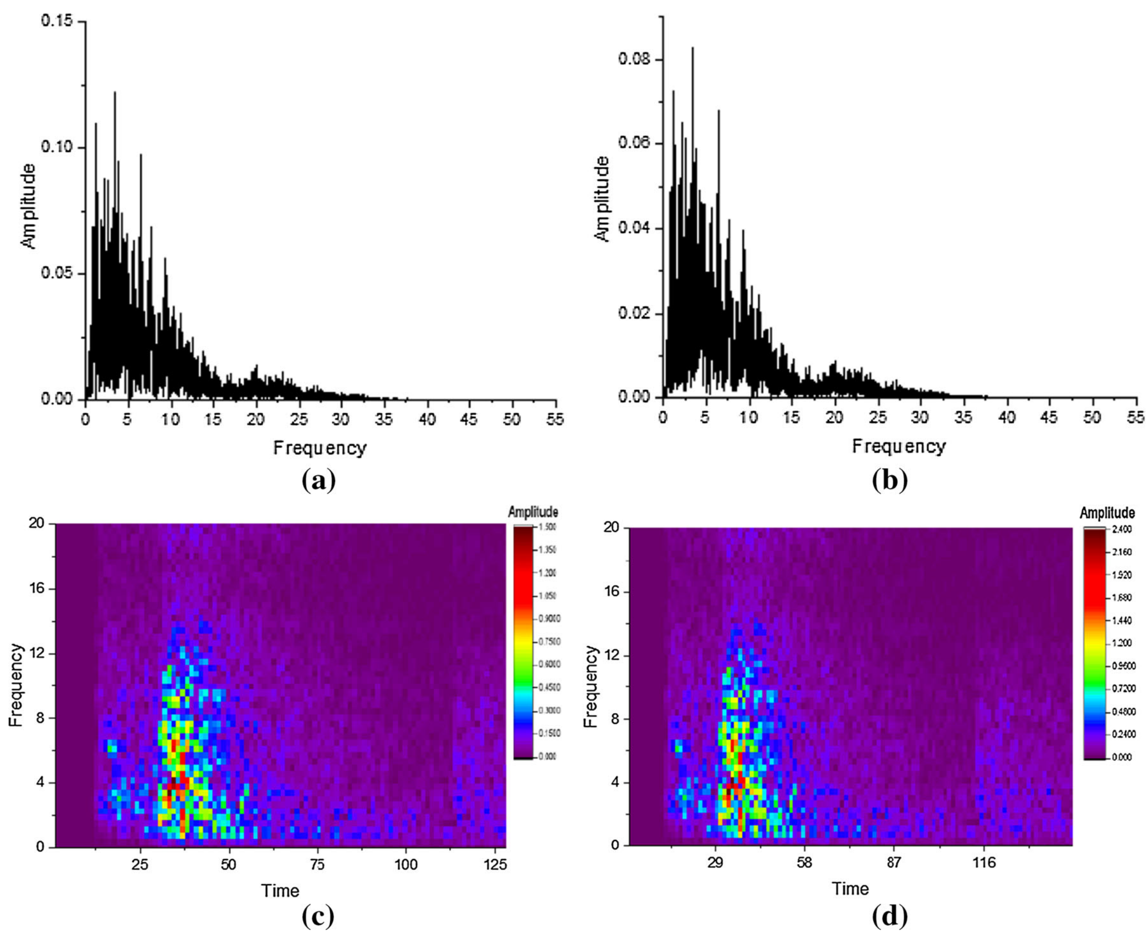


Fig. 35 FT and GT Spectrograms of signals in $M_{5.5–6.0}D_{201–240}$. **a** FT of actual signal in $M_{5.5–6.0}D_{201–240}$. **b** FT of synthetic signal for $M_{5.5–6.0}D_{201–240}$. **c** GT Spectrogram of actual signal in $M_{5.5–6.0}D_{201–240}$. **d** GT Spectrogram of the synthetic signal representing $M_{5.5–6.0}D_{201–240}$ [34]

observed that the frequency contents and their temporal variations were matching well.

A JTFA of seismic waves and its synthesis revealed interesting characteristics and features pertaining to the frequency contents and its temporal behaviour. Various JTFA techniques have been reviewed for applications in earthquake ground motions and a Linear JTFA technique, GT has been found well suited for analysis and GE has been adopted due to their advantages over other techniques for synthesizing acceleration time histories of scenario earthquakes in the region. A novel method for synthesizing earthquake motions where only limited data are available to predict a future scenario earthquake was presented.

Seismic Design of Geotechnical Structures

Seismic design of foundations, earth dams, retaining walls, embankments, and abutments are of high importance in geotechnical earthquake engineering to minimize the disastrous effects of earthquake hazards. The slope stability method using the pseudo-static approach for seismic loading is usually adopted for analysis of earth dams. Shallow foundations are also generally designed based on the bearing capacity estimated through pseudo-static approaches. Geotechnical structures, especially when constructed on sloping grounds, behave differently under seismic loading and this needs to be explored and understood. In such cases, the interaction between the structure and soil needs to be studied in detail [86].

Choudhury et al. [28] carried out a comprehensive review of various approaches used to estimate the seismic earth pressures and their point of application on earth retaining structures. The advantages and disadvantages of various design and analytical approaches for earthen dams and foundations under earthquake loading were discussed. Approaches like the force equilibrium based pseudo-static analysis, pseudo-dynamic analysis, and displacement-based sliding block methods were discussed. Considering a permissible wall displacement, force-based analysis, and displacement-based analysis were compared using numerical examples and it was found that displacement-based analysis was better. Based on the results, it was recommended that the IS code for the seismic design of retaining wall is to be reconsidered and modified.

The complex behaviour of piles embedded in sloping grounds under seismic loading was studied by Deendayal et al. [32]. The response of piles to dynamic loading is largely dependent on the soil–pile interactions on the interface of the pile surface. A plane strain Finite Element Analysis (FEM) of a single pile of 30 m length embedded in soft clay subjected to dynamic seismic forces was assessed by varying the slope and embedment length parameters. Various Length to Diameter (L/D) ratios like 20, 25, and 30 and slopes of 1 V:1H and 1 V:5H were studied. The behaviour of these piles in terms of acceleration vs time, bending moment, and lateral displacement along the pile shaft was studied. A bilinear Mohr–Coulomb model was adopted to model the soil–structure interaction and the pile was modeled as a linearly elastic beam element. An absorbent boundary was adopted to model the boundary conditions to avoid reflected dynamic interactions on the pile model. The time-history data from the California earthquake of 1990 was adopted as a model dynamic load. The varying effects of L/D ratios and ground slopes on maximum acceleration, displacement, and bending moments were reported and discussed. Figure 36 (a) shows the PLAXIS 2D model of a pile on soft clay sloping ground having an L/D ratio 30 and a slope of 1 V:1H. A similar approach was adopted to study the deformation and acceleration behaviour of piles subjected to static and dynamic loading by Deendayal et al. [89]. The seismic response of a single concrete pile of 11.5 m length and 0.4 m diameter located on a flat soft clay bed above a sand layer was studied using 2D PLAXIS models.

Experimental studies on the static lateral loading behaviour of laterally loaded single piles on soft clay sloping grounds were carried out by Deendayal et al. [33], Deendayal et al. [87], and Deendayal et al. [88]. Laboratory-scale model using aluminium piles with instrumentation was installed on varying slopes and L/D ratios like 1 V:1H, 1 V:1.5H, 1 V:2H, 1 V:3H, 1 V:5H and 20, 25, 30, respectively. Tests were carried out on the horizontal ground surface as well to understand the effect of slopes. Lateral loading capacity, load–deflection behaviour at pile head, the variation of pile load capacity for various embedment lengths and ground slopes, and bending-moment profile along the pile shaft were evaluated experimentally. PLAXIS 3D was used to study the pile with the above-mentioned L/D ratios and ground slopes using a FEM model and compare the experimental results. It was found that the experimental and FEM model results were comparable. Figure 36b presents the experimental setup used in the study.

Sitharam and Hegde [102] and Sitharam and Hegde [103] carried out a case study and probabilistic seismic slope stability analysis of a rockfill tailing dam in Rajasthan, India. Tailing dams are made of accumulated mining waste or slurry which are heaped over in layers and raised in due course of the deposition. They usually fail due to various factors like settlement, seepage, earthquakes, stress distribution, etc. In the case study discussed, the height of the tailing dam was supposed to be raised from 26 to 54 m as it had almost reached its capacity. Construction of a tailing dam could be carried out using different methods like upstream method, downstream method, and Centre-

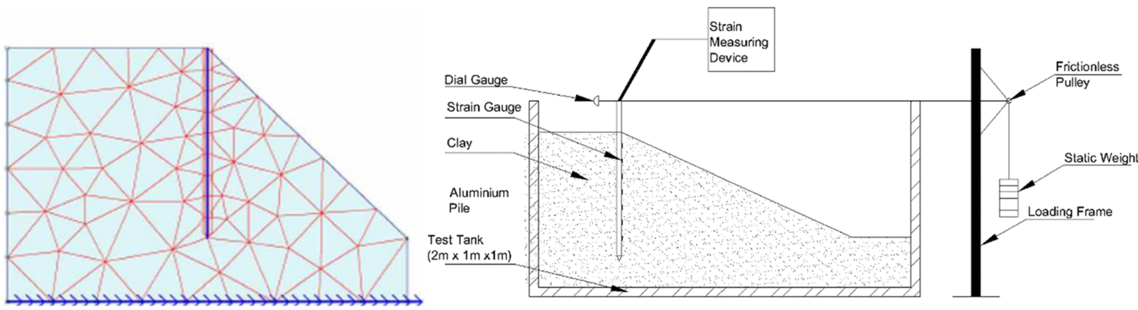


Fig. 36 **a** PLAXIS 2D model of a pile on soft clay sloping ground having *L/D* ratio 30 and slope of 1 V:1H [32]. **b** Experimental setup used for static analysis [89]

line method, each of which has its own merits and demerits. Selecting the best methods depends on the land availability, the soil at the site, properties of the tailings, etc. Monte–Carlo Simulation method (MCSM) was employed here for a seismic slope stability analysis using SLIDE to determine the FOS and mode of failure. A horizontal seismic acceleration coefficient of 0.06 g was adopted for seismic analysis. The downstream method was adopted in the study to raise the height of the embankment on the northern and eastern sides of the dam and, for every 6 m raise of the embankment, a seismic slope stability analysis was carried out. The FOS obtained using the adopted method was found to be much higher than the required value and the probability of failure of the dam was determined as 7.1–7.5% while adopting the downstream method [102]. Figure 37a shows the result of seismic slope stability analysis of the downstream slope at 51 m height with an acceleration coefficient of 0.06 g. On the other hand, the upstream method was adopted on the western side and a similar analysis was carried out. The dam is located in a Seismic zone II, and the slope stability analysis proved right and the design was found to be safe, as only small magnitude events were recorded in the area. The tailing dam has, as of now sustained five monsoons, without any failure reported to date. A linen HDPE geomembrane was also installed, which provides better sealing and frictional resistance, below which a thick aggregate layer was placed to provide better shear strength and stability. The proposed design was found to be seismic resistant, cost-effective, and environment friendly. Figure 37(b) shows the deformation vectors of the downstream slope from the FEM analysis. It has been further planned to increase the height of embankment from 54 m to 74 m in four phases using different methods and similar analyses.

Seismic loading on the built environment needs to be studied and understood, and attempts have been made towards the same by the author. The seismic response of geotechnical components and structures have been studied and quantified in past studies. The response of seismically loaded piles in various soil conditions and reliable seismic designs for structures like tailing dams have been undertaken successfully.

Srinivas et al. [141] carried out extensive studies and design for stabilizing highly jointed rock mass slopes of the world's highest railway bridge across the deep gorges of the Chenab river in the Himalayas. This bridge is the most critical component of the Udhampur Srinagar Baramulla Rail Link Project of Indian Railways, which is a project of national importance. The bridge is 1315 m long and has an arch span of 467 m with the deck at 362 m above the highest water level; which once completed, will be the world's highest railway bridge. The geology of the site is highly erratic with folds and faults and shear zones. The predominant strata at the site are highly jointed dolomite with shale bands. Further, the bridge is located in the most seismically active area, the Himalayas which is demarcated as Zone 5 in IS1893. Detailed site investigations comprising of trial pits, plate load tests, in situ direct shear tests, pull out tests, MASW tests, and response spectra analyses were carried out. Dynamic, static, and pseudo-static slope stability analyses were carried out using continuum analyses using *Slide* and *FLAC* for stability during the construction stage and long term stability. Based on the studies, elaborate slope stabilization measures have been employed using steel fibre-reinforced shotcrete, rock bolts, and double corrosion protected pre-stressed anchors using a top-down approach. The pre-stressed bar anchors were 33 m long anchors with a safe working load of 64T while the pre-stressed cable anchors were of 40 m length and with a safe working load of 100 MT. The rock excavation involved was more than 1 million cubic meters on deep slopes with a maximum depth of slope being 236.5 m on the left bank and 163.2 m on the right bank. The slopes have been now stabilized and the project is nearing completion with arch erection underway from both the banks of the river. Figure 38 shows the stabilized right bank of the river with arch erection in progress. The stabilized slope

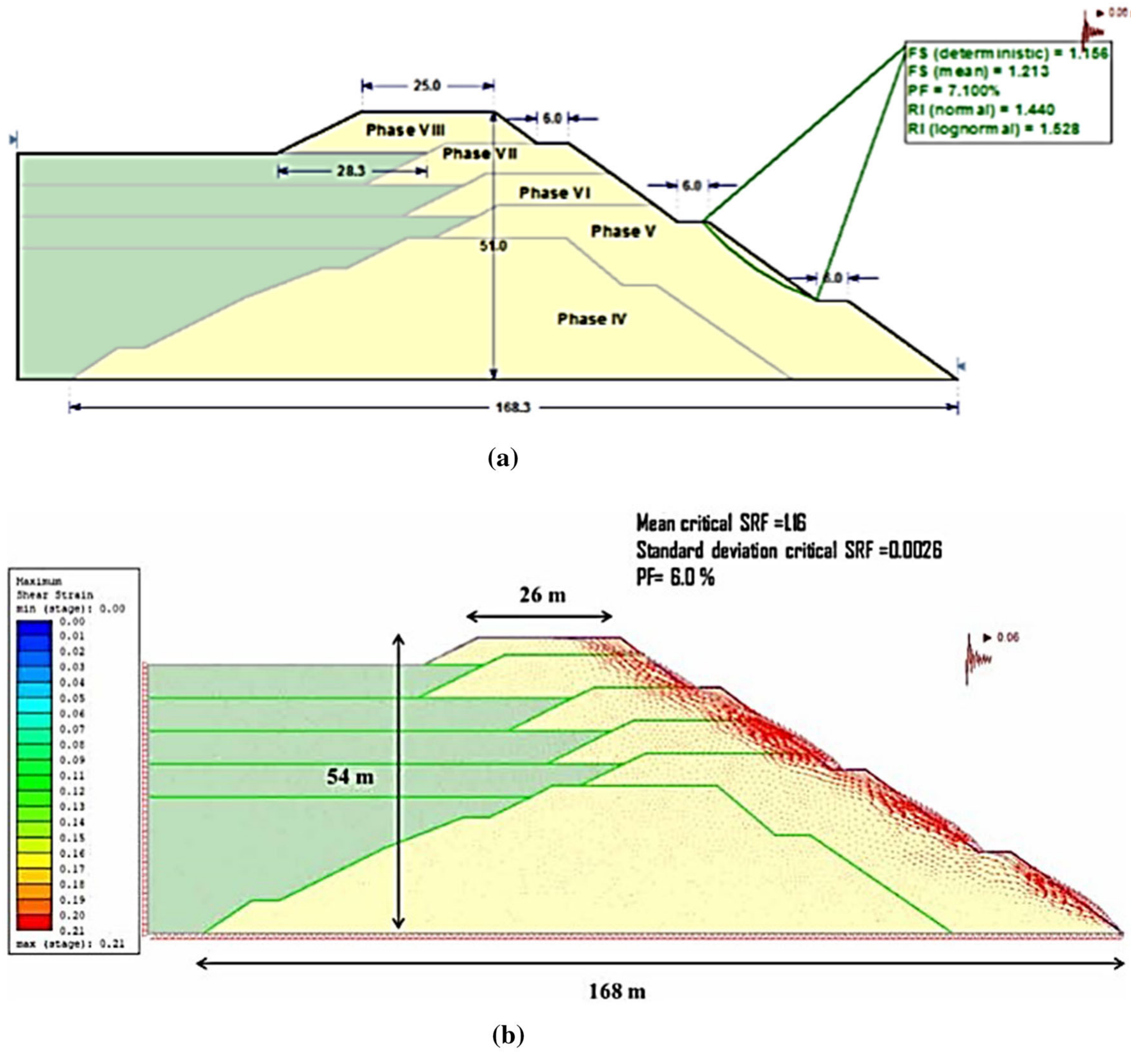


Fig. 37 **a** Seismic slope stability analysis of downstream slope at 51 m height of the embankment [102]. **b** Deformation vectors of the downstream slope from FEM analysis [103]

with rock bolts and excavations can be observed in the background.

Experimental and Numerical Studies on Dynamic Behaviour and Soil Liquefaction

Liquefaction susceptibility has been one of the major hazardous challenges in geotechnical engineering in earthquake-prone zones. Granular materials such as sands are the soil types that are usually most susceptible to liquefaction. To gain a better understanding of liquefaction and the mechanism involved at micro levels, numerical simulation using Discrete Element Modelling (DEM) can be considered as a good tool. It has enabled over time its application for a better understanding of the micromechanical behaviour of granular soils such as sands in drained and undrained loadings. Applications of DEM have helped to study the potential applications of 2D—Discrete Element Simulation to model the behaviour of reinforced granular soils [44].

Site-specific laboratory and analytical studies were undertaken by Sitharam et al. [124], where the behaviour of silty sand from Bhuj, Gujarat, India in terms of liquefaction susceptibility and dynamic properties were carried out. Sitharam et al. [118] presented the results of laboratory investigations carried out for liquefaction susceptibility and pore water pressure generation in samples collected from earthquake-prone areas of Ahmedabad, Gujarat, India using cyclic strain controlled triaxial tests. Effect of different parameters such as shear strain amplitude, initial effective confining pressure, relative density, and percentage of non-plastic fines on the behaviour of liquefaction and pore water pressure generation was studied in depth

Fig. 38 Stabilized right bank with arch erection in progress [141]

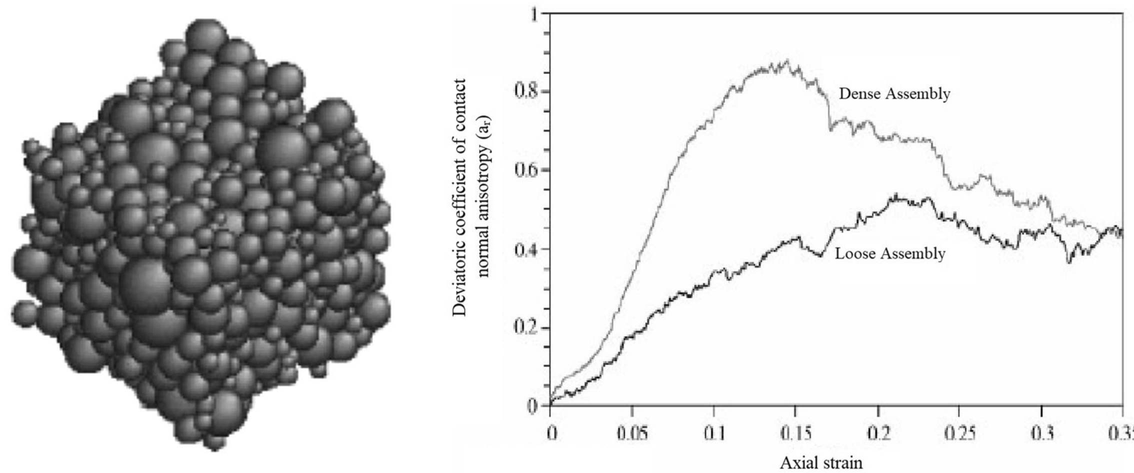
over these years. Further to study the effects of fines on pore pressure development during cyclic loading, Balreddy [20], studied the soil susceptibility to liquefaction using a series of stress-controlled cyclic triaxial undrained shear tests on reconstituted sand–fines mixtures.

Sitharam et al. [143] undertook a numerical simulation of 3-D DEM assemblies considering 1000 spherical particles under monotonic undrained (constant volume) and drained conditions. Special emphasis was laid on the study of micromechanical behaviour of phase transformation of medium dense sands which were modeled as 1000 spherical particles. The results obtained were further compared with characteristic lines representing zero dilatancy state in drained tests. An attempt to explain behaviour of the stress path for phase transformation was made using numerical modeling.

Sitharam et al. [145] undertook constitutive numerical simulation using a DEM, programmed in TRUBAL, to study isotropic compression and triaxial static shear tests under drained and undrained stress paths on the polydisperse assembly of loose and dense spheres representing granular soil particles. To study the micro–macro relationship, the micromechanical behaviour of loose and dense assemblies under drained and undrained conditions was undertaken. An attempt was made to micro-mechanically study the behaviour of granular material at the grain-scale level. Numerical simulations have been carried out using a DEM considering a 1000 sphere particle polydisperse assembly with periodic space representing an infinite three-dimensional space as shown in Fig. 39a. A series of numerical tests were undertaken using DEM on 3D assemblages of spheres to study the evolution of the internal variables such as induced anisotropy during deformation along with the macroscopic behaviour of the assemblage in drained and undrained shear tests. Figure 39(b) presents the variation of deviatoric coefficients with axial strain for different initial soil conditions. In a qualitative sense, the macroscopic stress–strain results and stress path evolution in these simulations using 3-D assemblies demonstrate that DEM simulations are capable of reproducing realistic compression and shear behaviour of granular materials [35].

Sitharam and Dinesh [142] studied the liquefaction behaviour of granular materials using numerical simulation using 3D DEM. 3D assemblies of 1000 polydisperse sphere particles using DEM were used to study the liquefaction behaviour of granular materials by undertaking simulations of cyclic triaxial shear tests in undrained conditions whereby the granular materials were simulated using the spherical particles. Different confining pressures under constant strain amplitude was considered for the numerical simulations. Figure 40 presents the q vs p stress paths for the undrained strain-controlled cyclic test for a confining pressure of 25 kPa. The simulations revealed that numerical modeling using 3D DEM could be used for qualitative and realistic macroscopic simulation for the cyclic behaviour of granular materials. It was observed in the numerical simulation that at low confining pressure the assembly liquefies rapidly under cyclic loading conditions while at higher confining pressure the separation between individual particles is prevented when granular materials tend to liquefy. It was inferred from the study that the magnitude of the applied cyclic stress decreases with an increase in confining pressure when compared to the undrained static strength. Dinesh et al. [91] adopted a similar methodology and further studied the seismic properties of soil such as damping ratio and reported a range of shear strain and confining pressures.

Sitharam et al. [124], studied the behaviour of silty sand from Bhuj, Gujarat, India in terms of liquefaction



(a) (b)

Fig. 39 **a** 3D view of the polydisperse assembly. **b** Deviatoric coefficients versus axial strain in drained shear test at a confining pressure of 50 kPa for samples under loose and dense initial conditions [145]

susceptibility. The dynamic properties of the soil were estimated under large shear strains ranging from 0.1% to 4%. Cyclic undrained shear tests were conducted for liquefied and oozed out soil samples which were collected from ground surface close to the epicentre of the Bhuj earthquake. From these tests, the dynamic properties were estimated at large strain levels of 0.5% to 4%. The modulus and damping estimated using cyclic triaxial testing at large strain levels can be considered to serve as key factors for the assessment of ground response due to earthquakes. From the experiments, it was further observed that at higher Cyclic Stress Ratios (CSR), the pore water pressure builds up fast and liquefaction is triggered at lower cycles of uniform load applications [38]. Figure 41 presents the rate of pore water pressure build-up with different CSR. An increase in the density increased the cyclic strength of soil, thereby making it less susceptible to liquefaction. A major reduction in the shear modulus and a corresponding increase in damping ratio occur in the large shear strain range exhibiting highly nonlinear behaviour. Based on the test results, it was observed that the relative density has no significant influence on the dynamic properties of soil in the large strain levels (beyond 1%), but it has a considerable influence at small strain levels (less than 1%).

Dinesh et al. [92] presented the results of the static behaviour of granular soils using 3D DEM simulations using 1000 sphere particles. Shear tests were modeled and carried out using spherical particles, thereby simulating stable granular assemblies at various initial conditions under drained, undrained, and constant pressure stress paths until critical state conditions were attained. The macroscopic results were presented with a micromechanical explanation and the validity of the stress-force-fabric relationship was presented. The results also indicated that in addition to the deviator stress, mean p, and volumetric strain, the average coordination number is constant at critical state.

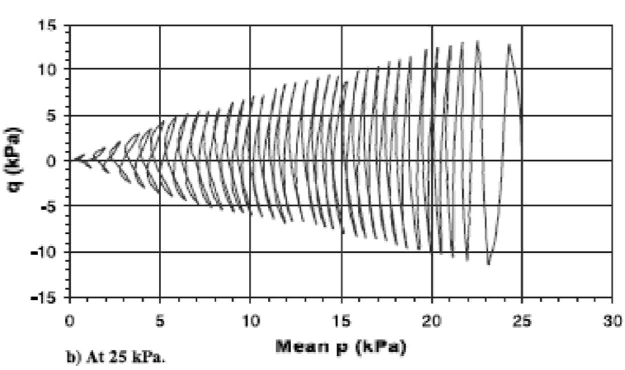


Fig. 40 Stress path in undrained strain-controlled (1%) cyclic test on a polydisperse sample at confining pressures of 25 kPa [142]

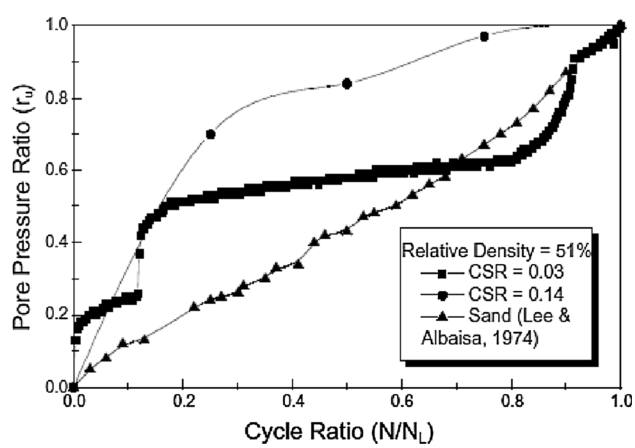


Fig. 41 Rate of pore water pressure build-up with CSR [124]

Sitharam et al. [118] presented the results of laboratory investigation carried out for liquefaction susceptibility and pore water pressure generation in soil samples collected from an earthquake-prone area of Ahmedabad, Gujarat, India using cyclic strain controlled triaxial tests. Effect of different parameters such as shear strain amplitude, initial effective confining pressure, relative density, and percentage of non-plastic fines on the behaviour of liquefaction and pore water pressure generation was studied. Based on the results, it was observed that the liquefaction susceptibility of the sandy soils was a function of considered parameters such as shear strain amplitude, initial relative density, initial effective confining pressure, and non-plastic fines [146]. Based on the obtained results, regression analysis was undertaken and empirical correlations were proposed for a wide range of cyclic strain, relative densities, and confining pressures. It was also observed that there is a relationship between pore pressure ratio and cycle ratio independent of relative density, confining pressure, the amplitude of shear strain, and percentage of non-plastic fines as shown in Fig. 42.

Vinod et al. [44], in their study, explored the potential application of 2D Discrete Element Simulation using PFC-2D to model the behaviour of reinforced granular soils. Biaxial element tests were carried out with and without horizontal reinforcement layers to understand the behaviour of reinforced granular soils from a microscopic grain-scale level. Numerical simulations were carried with assemblies of 1800 uniformly sized circular particles of dimensions 0.1 mm. For the study, the reinforcing elements were modelled using a chain of circular particles of considered dimension at predetermined contact locations and by further assigning contact bond between particles horizontally at the contact locations. Effect of parameters such as the number of reinforcement layers, the thickness of reinforcement layers, and packing geometry on the behaviour of reinforced granular materials was studied. It was observed that the improvement in the load-carrying capacity of the reinforced granular soils can be attributed to the restriction of the particle movement in the minor principal direction, by the reinforcement layer. It was also found that the development of tensile stresses in the reinforcement layer increases with the number of reinforcement layers similar to laboratory triaxial experiments. Figure 43 shows the spatial variation of contact force chains for different reinforcement configurations at a confining pressure of 100 kPa.

Samui and Sitharam [93] undertook a study to determine the liquefaction susceptibility of soil using AI techniques. The study predominantly used field tests i.e. Standard Penetration Test (SPT) and artificial intelligence (AI) tools i.e. artificial neural network (ANN) and Support Vector Machine (SVM) for predicting the liquefaction susceptibility of soils for a particular embankment site of ash pond in Raichur, India. ANN is a tool that was derived from similar functioning of the brain, which is connected using units called neurons and enables transmission of information within. The techniques enable us to consider various inputs and consequent outputs and allow us to train the machine to make further predictions based on them. The study also uses the SVM tool which has been primarily used as a classification tool. The inputs for this study using AI techniques were corrected SPT value and PGA which gave geotechnical and seismic input about the ground and allowed the user to predict and classify the liquefaction susceptibility of the ground. A comparative study has been

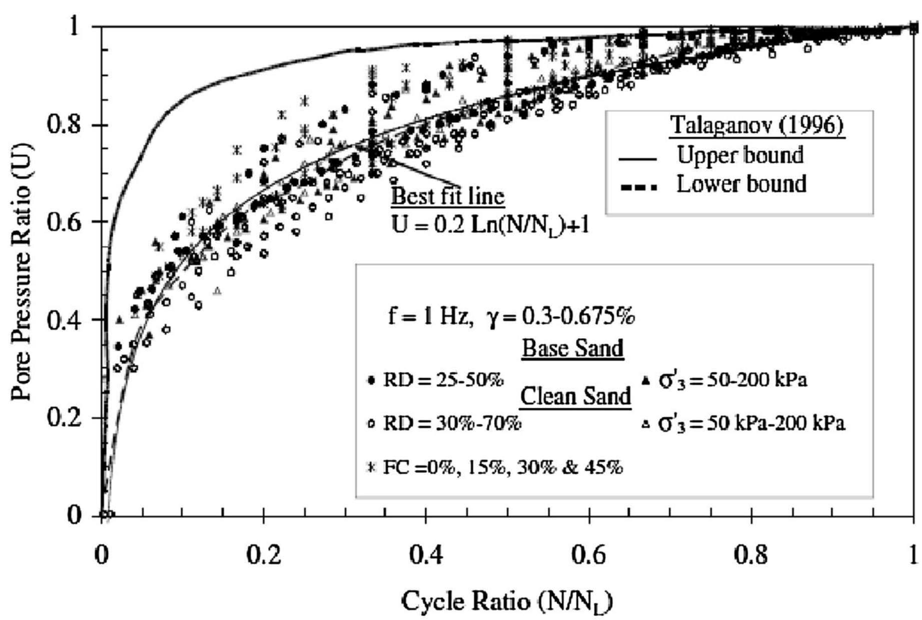


Fig. 42 Relationship between pore pressure ratio and cycle ratio for sand samples at various relative densities, confining pressure, percentage of silt content and a wide range of cyclic shear strain amplitudes [118]

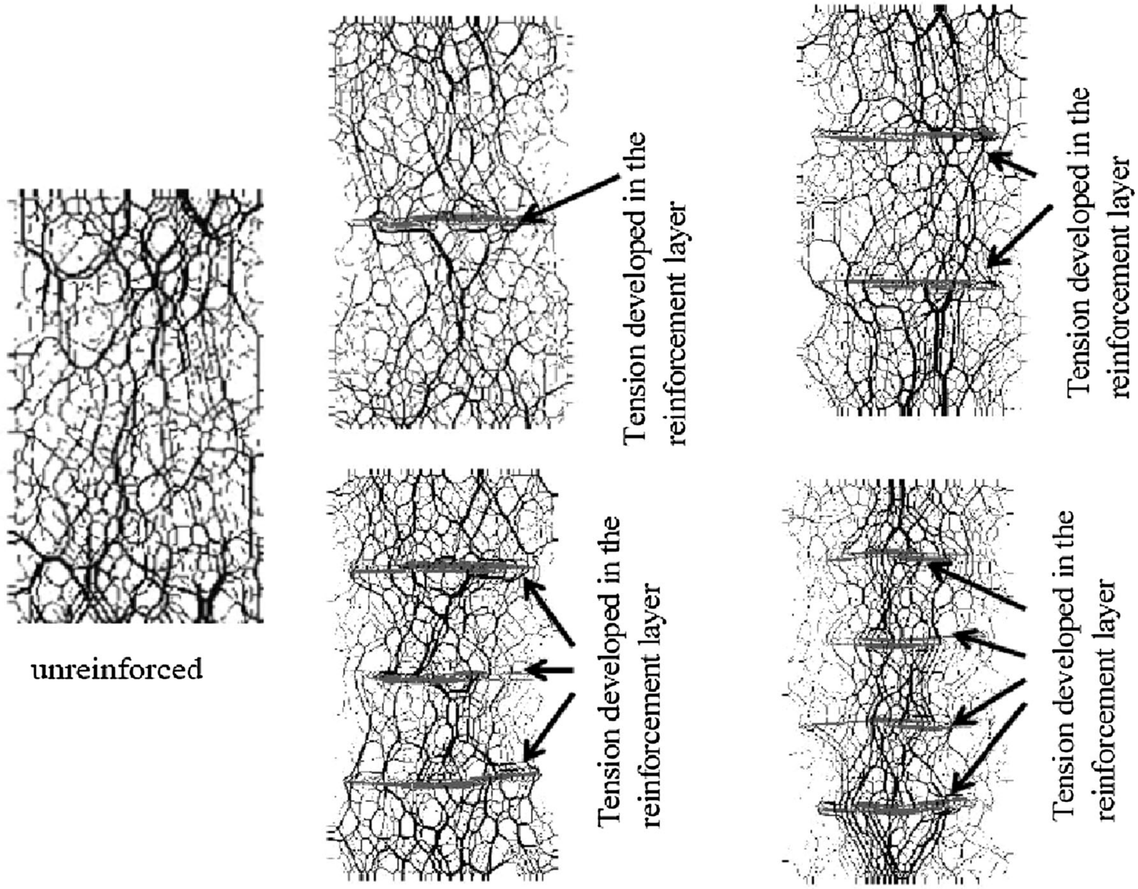


Fig. 43 Spatial variation of contact force chains for different reinforcement configuration at a confining pressure of 100 kPa [44]

further undertaken between field tests and AI techniques. The results suggest AI can be used as a good tool for such classifications and depicts that some portions of the site are highly susceptible to liquefaction [76].

Balreddy et al. [21] and Balreddy et al. [22] studied the effect of fines on pore pressure development during cyclic loading using a series of stress-controlled cyclic triaxial undrained shear tests conducted on a reconstituted sample of sand–fines mixtures. The prime consideration of the study was to evaluate the pore pressure build-up in the considered soil types to further study their susceptibility to liquefaction. For the study, the sand was procured from the Cauvery river bed, Karnataka and locally available low plasticity clay fines were used to prepare reconstituted sand–fines mixtures with the fine contents ranging from 0 to 30 percentages. The effect of cyclic loading in undrained conditions on sand-fine mix soil types and their susceptibility to liquefaction was assessed. It was observed that the soil mixes with low fine content failed by flow liquefaction whereas higher fine content showed a failure pattern by cyclic mobility. These results indicated that the presence of fines reduces the pore pressure build-up when compared to clean sand.

Experimental and analytical studies to assess the dynamic behaviour of soils are unavoidable in geotechnical earthquake engineering. Cyclic triaxial tests on undisturbed samples collected from the field and DEM of soil samples are necessary inputs in assessing the liquefaction susceptibility and understanding the soil–structure interaction during seismic loading. From various studies, the author quantified the effects of fines on pore pressure development during cyclic loading and studied the soil susceptibility to liquefaction. DEM was used to explain the behaviour of stress-paths and to study the evolution of the internal variables such as induced anisotropy during deformation along with the macroscopic behaviour of the assemblage in drained and undrained shear tests. It was found that DEM simulations are capable of reproducing realistic compression and shear behaviour of granular materials. Effect of various soil parameters liquefaction behaviour and pore water pressure generation were studied and it was observed that the liquefaction susceptibility of the sandy soils was a function of parameters like shear strain amplitude, initial relative density, initial effective confining pressure, and non-plastic fines. Further, attempts were made to assess liquefaction susceptibility of soil using AI techniques like

ANN and SVM and its suitability was proven for the specific problem.

Shock and Blast Loading behaviour of Granular Materials

Granular and porous materials-based protective layers have proven to be very good shock-absorbing mediums. Although sand material is widely used (as sandbags) till date in civil and military applications as a blast mitigating medium, the fundamental mechanism involved during the impact of shock/blast wave on sand layers is not well understood. To study this, Vivek and Sitharam [157] carried out experimental investigations on the impulsive response of sand to extreme loading conditions. A shock tube facility was used to generate a planar shock wave and further the facility was optimized to simulate the properties of a blast wave. The study was divided into three parts based on the type of loading imparted to the sand samples: shock loading, air-blast loading, and buried-blast loading. In part one—shock loading, the performance of the sand barrier systems in attenuating the shock waves was explored. The attenuation characteristics of various granular particles (coarse sand, fine sand, glass bead) were investigated by analysing the reduction in peak overpressure while being transmitted through the granular medium. The attenuating capability of the sand barriers had appreciably improved when the outer surfaces of the barriers were retrofitted with a geotextile layer. In the second part, a laboratory-scale experimental approach was presented for evaluating the effects of air-blast on the sand layers. Efforts have been made to study the stress wave propagation in loose and dense sand medium and its direct consequences on the vibrational response. Visualization of the sand deformation was possible with the help of a high-speed camera; displacement trajectories and strains contours were obtained through Digital Image Correlation (DIC) analyses. Part two also reviewed the applications of scaled air-blast study on buried pipelines. By using dimensional analysis procedure, shock tube experimental results were scaled up to predict the real scale damage imparted to the buried pipes during an air-blast explosion. Besides, a three-dimensional finite element analysis of the test condition was simulated using ABAQUS/Explicit to authenticate the fidelity of the scaling laws. The third part—buried blast loading, discussed the phenomenal aspects associated with the sand deposits when exposed to a buried blast explosion. Various events involved during the interaction of leading blast wave with the sand medium, and characterizing the outburst sand-ejecta were studied. The impulse and peak pressure imparted to the rigid target were evaluated using vertical pendulum and fast response pressure transducers. Parametric studies involving different target Stand-off Distance (SoD) with various Depth of Burial (DoB) of the blast were presented in the study. It was found from the study that sand ejecta has a greater influence on the impulse at higher SoDs ($>$ 40 mm) and the maximum momentum transfer is observed when SoD-to-DoB ratio is 2.5 [156]. Figure 44 presents the DIC computed strain contour for loose sand and Fig. 45 presents the evolution of sand ejecta for 32 mm DoB imaged at various time intervals.

Earthquake Preparedness

Sitharam and Kolathayar [116] with the vision of safeguarding the lives of people and minimizing the loss of property due to earthquake, presented their book titled Preparing for Earthquakes: Lessons for India [116]. This book endorsed by the Indian Society of Earthquake Technology (ISET) presents the action plans to be undertaken by the general public and public agencies before, during, and after an earthquake event to reduce the disaster risk. The authors presented general guidelines for individuals and families in case of an earthquake on how to respond before, during, and after an event. Specific guidelines for households, schools, and business organizations were presented along with a note to the public policymakers. The current scenario and the way forward on how to achieve a prepared community and reduce the loss of lives and assets were discussed in detail. A detailed action plan for how to develop a resilient community for earthquake preparedness, from forming a good team, understanding the hazard, creating awareness to organizing community outreach programs were discussed. A survey-based Earthquake Readiness Index (ERI) tool for India was presented and different earthquake readiness indices ranges were presented from 0 to 27, representing very poor to an excellent degree of preparedness. The tool was designed in such a way that a user could identify on which aspects of preparation more effort has to be taken to be actively prepared for a major earthquake. Based on the survey conducted, a comparison of the demographics-based mean indices at individual and community level was presented and the same is depicted in Fig. 46.

Development of Facilities—Seismic Broadband Station, Cyclic Triaxial Equipment, Piezo-Vibro-Cone System, Shake Table, Laminar Box

In an attempt to monitor the seismic activity and continuously contribute to the Indian strong-motion network, a Broad Band Sensor (BBS) was installed at the IISc campus by the author and his team. A BBS is a precise earthquake

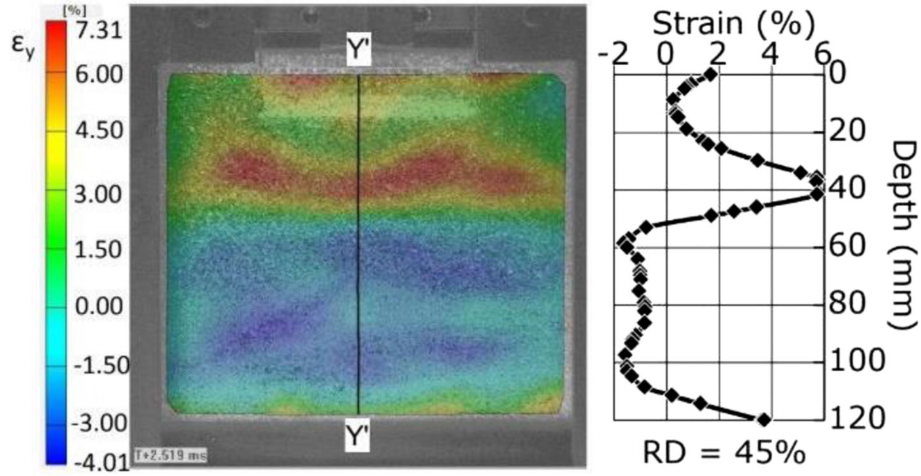


Fig. 44 DIC computed strain contour for loose sand (Graph presents the variation of strain along section Y–Y) [156]

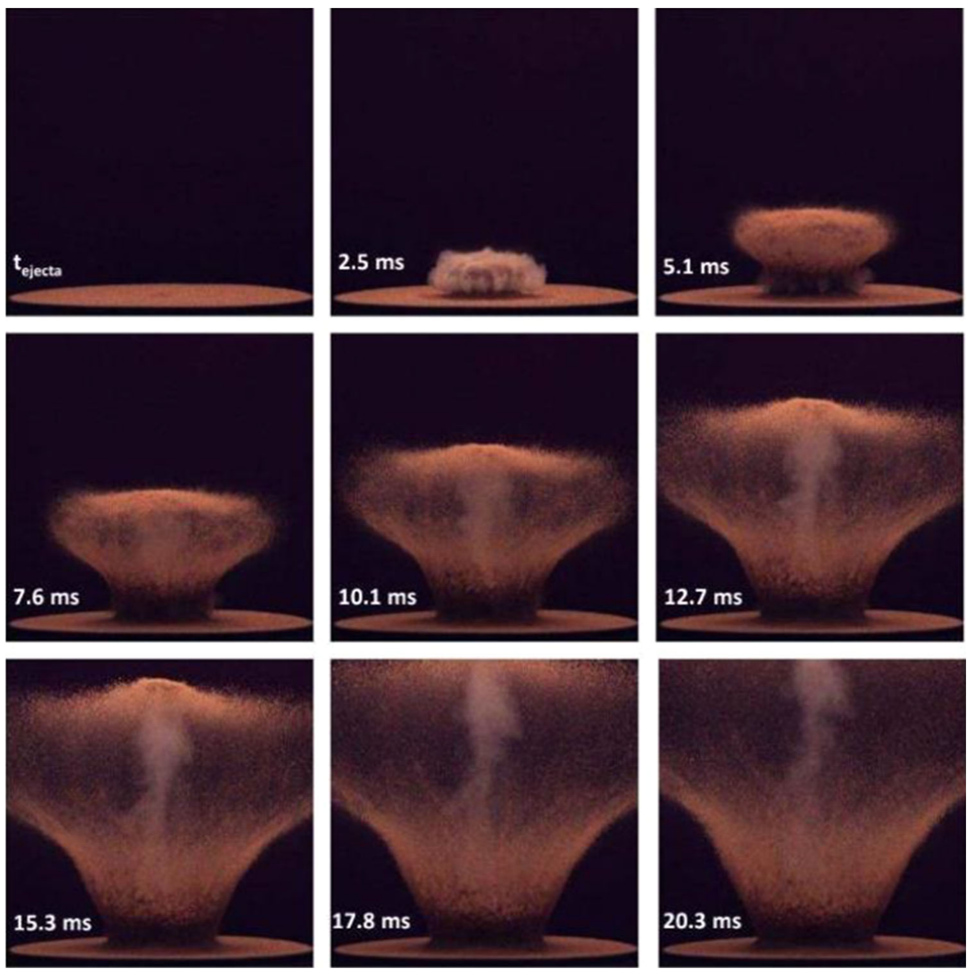


Fig. 45 Evolution of sand ejecta for 32 mm DoB imaged at various time intervals [156]

monitoring equipment consisting of a velocity sensor, recorder, hard disk, and a GPS. The sensor was installed inside a small building on a hard bedrock outcrop inside the IISc campus. Figure 47 shows the BBS setup installed in the IISc campus. Further, IISc had procured 8 Strong Motion Accelerographs (SMA) and installed them at various sites on the campus. These include 6 strong-motion and 2 shallow borehole triaxial force balance accelerometers with 40 m cables. These accelerographs have a timing accuracy of 0.5 ms due to synchronized sampling, 18 bits resolution, and a dynamic range of 108 dB. The SMAs have a full-scale range of ± 2 g and a trigger bandwidth of

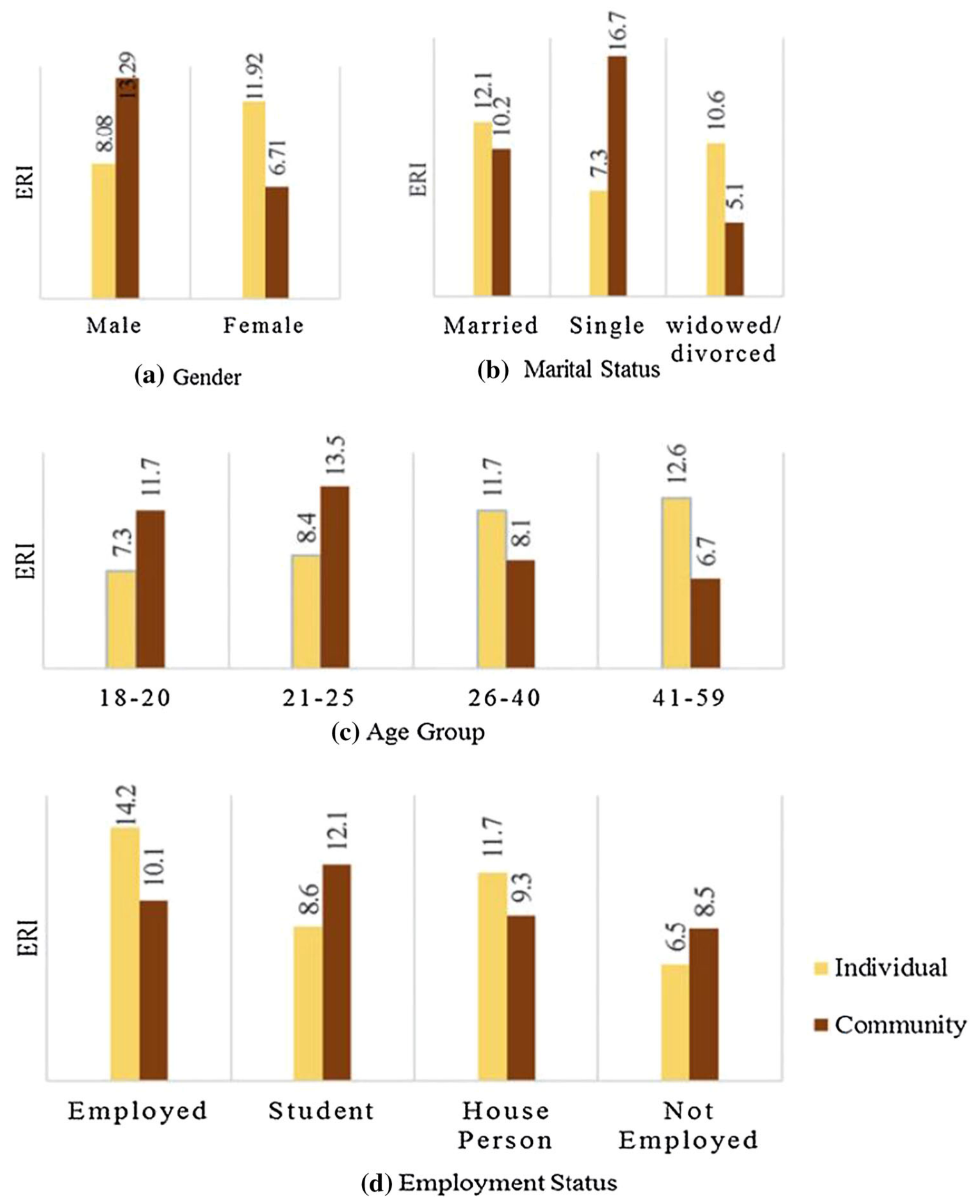


Fig. 46 A comparison of the demographics-based mean indices at the individual and community level [116]

Fig. 47 BroadBand Sensor installed in IISc campus

0.1–12.5 Hz. Figure 48a, b shows the SMA and borehole sensors installed in the IISc campus.

Further, a state of the art cyclic triaxial testing facility, piezo-vibro-cone system, a uniaxial shake table facility and a laminar box was developed and installed in the Soil mechanics laboratory of the Department of Civil Engineering in IISc campus. The completely automated and computerized cyclic triaxial testing facility was thereafter used to study the behaviour of soils subjected to dynamic loading, liquefaction behaviour and also to estimate the dynamic soil properties such as shear modulus (*G*) and damping (*D*) required for the design of geotechnical structures subjected to earthquake loading. A servo-controlled piezo-vibro-cone equipment consisting of a cone penetrometer coupled with a hydraulic shaker to induce

(a) (b)

Fig. 48 **a** SMA and **b** Borehole Sensor installed in IISc campus

liquefaction locally in the vicinity of the probe during penetration at desired depth was developed by the author. The indigenously developed piezo-vibro-cone has three built-in sensors, a load cell for tip resistance, load cell for skin resistance, and a piezo-sensor for pore pressure measurement. A shake table of usable size 1 m × 1 m, with provisions for hydraulic actuators, velocity and acceleration transducers, alternative top plates to represent different roughness of the table–model structure interface, and a 30kN servo-actuator for the horizontal motion were also developed with key inputs from the author. A laminar box that incorporates the idea of rotation of endplates was also designed installed in the laboratory.

Outreach Activities

The author has been very active in supporting the various State and National Disaster Management Authorities (SDMA and NDMA) and other government bodies with timely reports on the studies of various earthquakes, their effects, site studies, preparedness and more, especially during the Bhuj earthquake of 2001 and Nepal earthquake of 2015. The author acted as the Chairman of the Working Committee of Experts formed by NDMA, to prepare the national guidelines for geotechnical/geophysical tests for seismic microzonation in India. The author has executed several projects related to geotechnical earthquake engineering, funded by the Ministry of Earth Sciences Govt. of India, ISRO, BRNS, DST, and industry. Continuous efforts are made for the last two decades to raise public awareness in the field of earthquake engineering and preparedness through interviews, interactions, webinars, newspaper articles, and social media. To name a few, recent articles like 'On shaky ground' in *the pioneer* (Aug 6, 2020) and 'Recent earthquakes not unusual but disaster management plans needed in Delhi: Experts' in *The Print* (June 7, 2020) have stressed the author's statements in preparing the communities to face earthquakes and the importance of earthquake-resistant designs.

Conclusion

Geotechnical considerations are crucial in the successful design of any part of the built environment. There is a strong need to raise awareness on the importance of the application of geotechnical skills and knowledge in every aspect of building developments. This will involve the following: a review of the geological, seismological, and geotechnical context of the development site; specific investigation and gathering of geotechnical and related data; development of geotechnical design parameters appropriate to the building development and the site; due account of geotechnical considerations in the design of the building development so that it meets the requirements of the building code; due consideration of geotechnical factors, including overall land stability, before the issue of resource and building consents; review of geotechnical conditions and modification of design details as necessary during construction. DEM and simulation of the dynamic behaviour of soils were carried out and it was found to closely represent the actual soil behaviour when compared with laboratory and field dynamic tests on the soil

[35, 38, 146]. Similar was the case with the application of ANN and SVM towards liquefaction studies [76]. These could be effectively utilized for liquefaction studies and in estimating the susceptibility. Comprehensive seismic hazard studies, site characterization, liquefaction susceptibility, and microzonation was carried out in the macro-level for the whole country, Himalayan region, and the peninsular region, and in the meso level for states like Karnataka, Sikkim, Tripura, Mizoram and in the micro-level for cities like Lucknow, Bangalore, Mangalore, Delhi, Agartala, etc. [1, 5, 19, 51, 67, 69, 78, 140]. Region-specific GMPEs were developed, using which SHA was carried out for the Indo Gangetic Basin region and the North and North East Himalayas [1, 67, 78]. Recent developments in JTFA techniques were also explored and effectively used to synthesize reliable ground motion for the Himalayan region for scenario earthquakes; without compromising the quality of the frequency contents of the signals [78]. With a vision of 'Zero tolerance to avoidable deaths due to earthquakes', significant contributions were made by the author in the field of Geotechnical Earthquake Engineering, which helped to revamp the perception towards earthquake studies and the need for better design and preparedness in the country.

Acknowledgment I would like to acknowledge and thank all my Ph.D. students for their untiring efforts towards bringing out the best in them, and contributing to my vision and philosophy. I would like to acknowledge the contributions from Dr. Deepankar Choudhury, Dr. Dinesh S. V., Dr. Govindaraju L., Dr. Vinod J. S., Dr. Pijush Samui, Dr. Anbazhagan P., Dr. K. S. Vipin, Dr. Abhishek Kumar, Dr. Sreevalsa Kolathayar, Dr. Naveen James, Dr. Arjun Sil, Dr. Deendayal Rathod, Dr. Bala Reddy Muthanna, Dr. Vivek P., Dr. Monalisha Nayak and Mr. Ramkrishnan R. I would like to acknowledge the help received from Mr. Ramkrishnan R. and Dr. Sreevalsa Kolathayar in preparing this lecture and thank them. I extend my warm gratitude to all the funding agencies who have financially supported my research works so far and all the colleagues who worked with me on this topic from India and abroad. I would like to thank IGS for awarding me the IGS- Kueckelmann award in 2015 and also selecting me for delivering this annual lecture in 2020. I thank the Indian Society of Earthquake Technology (ISET) for their continuous support. I would further like to thank everyone who has supported and submitted their papers to the forthcoming 7th International Conference on Recent Advances in Geotechnical Earthquake Engineering (ICRAGEE).

References

1. Abhishek K (2013) Seismic microzonation of lucknow based on region specific GMPE's and geotechnical field studies. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
2. Alvarez L, Vaccari F, Panza GF (1999) Deterministic seismic zoning of eastern Cuba. Pure appl Geophys 156(3):469–486
3. Anbazhagan P, Sitharam TG (2008) Site Characterization of Bangalore using Geophysical Method. In: 3rd International Conference on Site Characterization, Taipei, Taiwan, Taipei
4. Anbazhagan P, Sitharam TG, Divya C (2007) Site Response Analyses based on Site Specific Soil Properties using Geotechnical and Geophysical tests: Correlations between Vs30, Gmax and N60. In: 4th International Conference on Earthquake Geotechnical Engg., Thessaloniki, Greece, June 25–28, 2007, Greece
5. Anbazhagan P (2007) Site characterization and Seismic hazard Analysis with local site effects for Microzonation of Bangalore. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
6. Anbazhagan P, Abhishek K, Sitharam TG (2011) Amplification from Isoseismal Map and Site Response Analysis. Third Indian Young Geotechnical Engineers Conference (3IYGEC), 25–26 March 2011, Indian Geotechnical Society, New Delhi
7. Anbazhagan P, Abhishek K, Sitharam TG (2013) Ground motion prediction equation considering combined dataset of recorded and simulated ground motions. Soil Dyn Earthq Eng 53:92–108
8. Anbazhagan P, Abhishek K, Sitharam TG (2013) Seismic site classification and correlation between standard penetration test N value and shear wave velocity for Lucknow City in Indo-Gangetic Basin. Pure Appl Geophys 170(3):299–318
9. Anbazhagan P, Sitharam TG (2006) Evaluation of dynamic properties and ground profiles using MASW: correlation between Vs and N60. In: Proceedings of 13th Symposium on Earthquake Engineering, Indian Institute of Technology, Roorkee, December. 2006
10. Anbazhagan P, Sitharam TG (2010) GIS & RS Integration For Microzonation Hazard Mapping. In: 11th ESRI India user conference 2010
11. Anbazhagan P, Sitharam TG (2008) Seismic microzonation of Bangalore, India. J Earth Syst Sci 117(2):833–852
12. Anbazhagan P, Sitharam TG (2008) Site characterization and site response studies using shear wave velocity. J Seismol Earthq Eng 10(2):53–67
13. Anbazhagan P, Sitharam TG (2008) Site characterization studies of Bangalore using a geophysical method. Geotechnical and Geophysical Site Characterization. Taylor and Francis Group, London
14. Anbazhagan P et al (2010) Multi-criteria seismic hazard evaluation for Bangalore city, India. J Asian Earth Sci 38(5):186–198
15. Anbazhagan P, Vinod JS, Sitharam TG (2009) Probabilistic seismic hazard analysis for Bangalore. Nat Hazards 48(2):145–166
16. Anbazhagan P, Sitharam TG, Divya C (2006) Site amplification and liquefaction studies for Banglore City. Indian Geotechnical Conference
17. Anbazhagan P, Sitharam TG, Vipin KS (2009) Site classification and estimation of surface level seismic hazard using geophysical data and probabilistic approach. J Appl Geophys 68(2):219–230
18. Anbazhagan P, Vinod JS, Sitharam TG (2007) Probabilistic seismic hazard analysis with local site effects. In: A Workshop on Microzonation, 2007, Bangalore, pp 122–138
19. Arjun S (2014) Seismic Hazard Assessment of Tripura and Mizoram States along with microzonation of Agartala and Aizawl cities. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
20. Bala RM (2018) Liquefaction and Post Liquefaction Behaviour of Sand-Fines Mixtures. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
21. Balreddy MS, Dinesh SV, Sitharam TG (2015) Effect of plastic and non-plastic fines on liquefaction resistance of sandy soils, 50th IGC, 2015. Pune, Maharashtra
22. Balreddy MS, Dinesh SV, Sitharam TG (2019) Effect of fines on pore pressure development during cyclic loading. In: Adimoolam B, Banerjee S (eds) Soil dynamics and earthquake geotechnical engineering. Lecture Notes in Civil Engineering, vol 15. Springer, Singapore

23. Bansal BK, Vandana C (2007) Microzonation Studies in India: DST initiatives. In: Proceedings of workshop on microzonation, Indian Institute of Science Bangalore, pp 1-6
24. Bhatia SC, Kumar MR, Gupta HK (1999) A probabilistic seismic hazard map of India and adjoining regions. Ann Geofis 42(6):1153–1164
25. Burnwal ML, Burman A, Samui P, Maity D (2017) Deterministic strong ground motion study for the Sitamarhi area near Bihar-Nepal region. Nat Hazards 87(1):237–254
26. Bus Z, Szeidovitz G, Vaccari F (2000) Synthetic seismogram based deterministic seismic zoning for the Hungarian part of the Pannonian basin. Seismic hazard of the circum-pannonian Region. Birkhäuser, Basel, pp 205–220
27. Cetin KO, Seed RB, Der Kiureghian A, Tokimatsu K, Harder LF Jr, Kayen RE, Moss RE (2004) Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. J Geotech Geoenviron Eng 130(12):1314–1340
28. Choudhury D, Sitharam TG, Subba Rao KS (2004) Seismic design of earth-retaining structures and foundations. Curr Sci 1:1417–1425
29. Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 58(5):1583–1606
30. Cramer CH (2001) A seismic hazard uncertainty analysis for the New Madrid seismic zone. Eng Geol 62(1):251–266
31. Das S, Ghosh S, Kayal JR (2019) Liquefaction potential of Agartala City in Northeast India using a GIS platform. Bull Eng Geol Env 78(4):2919–2931
32. Deendayal R, Muthukkumaran K, Sitharam TG (2016) Response of laterally loaded pile in soft clay on sloping ground. Int J Geotech Eng 10(1):10–22. https://doi.org/10.1179/1939787915y.0000000013
33. Deendayal R, Sitharam TG, Muthukkumaran K (2016) Effect of Earthquake on a single pile located in sloping ground. Int J Geotech Earthq Eng (IJGEE) 7(1):57–72
34. Devaraj D, Ramkrishnan R, Prabu T, Kolathayar S, Sitharam TG (2020) Synthesis of Linear JTFA Based Response Spectra for Structural Response and Seismic Reduction Measures for North-East India. Journal of Earthquake and Tsunami
35. Dinesh SV (2003) Discrete element simulation of static and cyclic behaviour of granular materials. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
36. El-Sayed A, Vaccari F, Panza GF (2001) Deterministic seismic hazard in Egypt. Geophys J Int 144(3):555–567
37. Geotechnical/Geophysical Investigations for Seismic Microzonation Studies of Urban Centres in India, Technical Report, NDMA, 2011
38. Govindaraju L (2005) Liquefaction and Dynamic Properties of Sandy Soils. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
39. Govindaraju L, Bhattacharya S (2008) Site response studies for seismic hazard analysis of Kolkata city. In: Proceedings of 12th international conference of international association for computer methods and advances in geomechanics, pp 2899–2907
40. Gupta ID (2002) The state of the art in seismic hazard analysis. ISET J Earthq Technol 39(4):311–346
41. Gutenberg B, Richter CF (1956) Earthquake magnitude, intensity, energy, and acceleration: (Second paper). Bull Seismol Soc Am 46(2):105–145
42. Hough SE, Roger B (2008) Site response of the Ganges basin inferred from re-evaluated macroseismic observations from the 1897 Shillong, 1905 Kangra, and 1934 Nepal earthquakes. J Earth Syst Sci 117(2):773–782
43. Iwasaki T, Tokida K, Tatsuoka F, Watanabe S, Yasuda S, Sato H (1982) Microzonation for soil liquefaction potential using simplified methods. In: Proceedings of the 3rd international conference on microzonation, Washington, DC, pp 1319–1330
44. Vinod JS, Sharat N, Sitharam TG, Dinesh SV (2011) Numerical Simulation of reinforced granular soils using DEM. Geo-Frontiers 2011 ASCE 2011
45. James N, Sitharam TG (2014) Assessment of seismically induced landslide hazard for the State of Karnataka using GIS technique. J Indian Soc Rem Sens 42(1):73–89
46. James N, Sitharam TG (2015) Macro-level assessment of seismically induced landslide hazard for the State of Sikkim, India based on GIS technique. IOP Conf Ser Earth Environ Sci 26(1):2015
47. James N, Sitharam TG (2016) Seismic zonations at micro and macro-level for regions in the peninsular India. Int J Geotech Earthq Eng (IJGEE) 7(2):35–63
48. James N et al (2014) Seismic microzonation of a nuclear power plant site with detailed geotechnical, geophysical and site effect studies. Nat Hazards 71(1):419–462
49. James N, Sitharam TG, Vipin KS (2011) Assessment of liquefaction potential for karnataka state using probabilistic approach. In: Proceedings of Indian Geotechnical Conference, December 15-17, 2011, Kochi
50. James N, Sitharam TG, Vipin KS (2012) Assessment of liquefaction potential index using deterministic and probabilistic approaches. Int J Geotech Earthq Eng (IJGEE) 3(2):60–76
51. Vipin KS (2010) Assessment of seismic hazard with local site effects: Deterministic and probabilistic approaches. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
52. Kolathayar S, Sitharam TG (2012) Characterization of regional seismic source zones in and around India. Seismol Res Lett 83(1):77–85
53. Kolathayar S, Sitharam TG (2012) Comprehensive probabilistic seismic hazard analysis of the Andaman-Nicobar regions. Bull Seismol Soc Am 102(5):2063–2076
54. Kolathayar S, Sitharam TG (2011) Probabilistic evaluation of seismic hazard in and around Kerala. In: Proceedings of Indian Geotechnical Conference, December 15–17,2011, Kochi
55. Kolathayar S, Sitharam TG (2018) Earthquake hazard assessment: India and adjacent regions. CRC Press, Boca Raton
56. Kolathayar S, Sitharam TG, Vipin KS (2010) Deterministic seismic hazard macrozonation of India. J Earth Syst Sci 121(5):1351–1364
57. Kolathayar S, Sitharam TG, Vipin KS (2014) Probabilistic liquefaction potential evaluation for India and adjoining areas. Indian Geotech J 44(3):269–277
58. Kramer SL (1996) Geotechnical earthquake engineering. Pearson, London
59. Krinitzsky EL (2003) How to combine deterministic and probabilistic methods for assessing earthquake hazards. Eng Geol 70(2):157–163
60. Kumar A (2002). Generation of spectrum compatible time-history. In: Proceedings of 12th Symposium on Earthquake Engineering
61. Kumar A, Anbazhagan P, Sitharam TG (2013) Liquefaction hazard mapping of Lucknow: a part of Indo-Gangetic Basin (IGB). Int J Geotech Earthq Eng (IJGEE) 4(1):17–41
62. Kumar A, Anbazhagan P, Sitharam TG (2013) Seismic hazard analysis of Lucknow considering local and active seismic gaps. Nat Hazards 69(1):327–350
63. Kumar BS, Anbazhagan P, Sitharam TG (2006) Development of theoretical dispersion curves and comparison with multichannel analysis of surface waves (MASW). In: 13 th Symposium on Earthquake Engineering. Indian Institute of Technology, Roorkee. 2006

64. Kwok AO, Stewart JP, Hashash YM (2008) Nonlinear ground-response analysis of Turkey Flat shallow stiff-soil site to strong ground motion. Bull Seismol Soc Am 98(1):331–343
65. McGuire RK (2004) Seismic hazard and risk analysis. Earthquake Engineering Research Institute
66. Molden D, Sharma E, Acharya G (2016) Lessons from Nepal's Gorkha earthquake 2015. Lessons from Nepal's earthquake for the Indian Himalayas and the Gangetic plains, pp 1–14
67. Monalisha N (2019) A revisit to seismic hazard analyses of North India with local site effects. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
68. Nath SK (2007) Seismic Microzonation Framework—Principles & Applications. In: Proceedings of Workshop on Microzonation, Indian Institute of Science, Bangalore, pp 9–35
69. Naveen J (2014) Site characterization and assessment of various earthquake hazards for micro and macro-level seismic zonations of regions in the peninsular India. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
70. Naveen BP, Sitharam TG, Sivapullaiah PV (2015) Seismic analysis of municipal solid waste landfill in India. Int J Geotech Earthq Eng (IJGEE) 6(2):35–55
71. Naveen BP, Sitharam TG, Sivapullaiah PV (2019) Seismic behavior and dynamic site response of municipal solid waste landfill in India. Recent challenges and advances in geotechnical earthquake engineering. IGI Global, pp 168–196
72. Nayak M, Sitharam TG (2019) Estimation and spatial mapping of seismicity parameters in western Himalaya, central Himalaya and Indo-Gangetic plain. J Earth Syst Sci 128(3):45
73. Nayak M, Sitharam TG, Kolathayar S (2015) A revisit to seismic hazard at Uttarakhand. Int J Geotech Earthq Eng (IJGEE) 6(2):56–73
74. NEHRP Recommended Provisions for seismic Regulations for New buildings and other Structures, Part1: Provisions, FEMA 368, Federal Emergency Management Agency, Washington, DC, BSSC, 2003
75. PCRSMJUA (2005) Project Completion Report of Seismic Microzonation of Jabalpur Urban Area. Department of Science and Technology, Government of India, India.2 volumes
76. Pijush S (2007) Geotechnical Site Characterization and Liquefaction evaluation using Intelligent models. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
77. Rajiv R (2005) Seismic Response Analysis of Dehradun city, India. M.Sc Thesis, International Institute for Geo-Information Science and Earth Observations -Enschede, Netherlands, p 86
78. Ramkrishnan R (2020) Attenuation characteristics and seismicity analysis of himalayan region with linear joint time-frequency analysis techniques. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
79. Ramkrishnan R, Deepa D, Sreevalsa K, Sitharam TG (2020) Joint time frequency analysis based synthesis of acceleration-time history and response spectra for Japanese earthquakes. In: 7th International conference on recent advances in geotechnical earthquake engineering and soil dynamics ICRAGEE 2020, Bangalore, India
80. Ramkrishnan R, Deepa D, Sreevalsa K, Sitharam TG (2020) Recent developments in synthesis of earthquake motions using linear joint time frequency analysis techniques. In: 17th World conference on earthquake engineering, 17WCEE 2020, Sendai, Japan
81. Ramkrishnan R, Kolathayar S, Sitharam TG (2018) New attenuation relations for the North East Himalayas. In: 16th Symposium on earthquake engineering, ISET, IIT Roorkee, Dec 2018
82. Ramkrishnan R, Kolathayar S, Sitharam TG (2020) Linear joint time frequency analysis based simulation of earthquake motions for north and Central Himalayas. Geophys J Int (Under Review)
83. Ramkrishnan R, Kolathayar S, Sitharam TG (2019) Development of new ground motion prediction equation for the north and central himalayas using recorded strong motion data. J Earthq Eng 1:1–24
84. Ramkrishnan R, Kolathayar S, Sitharam TG (2020) Strong motion data based regional ground motion prediction equations for north east india based on non-linear regression models. J Earthquake Eng 1:1–21
85. Ramkrishnan R, Sreevalsa K, Sitharam TG (2019) Seismic hazard assessment and land use analysis of Mangalore City, Karnataka, India. J Earthq Eng 1:1–22
86. Rathod D (2016) Analysis of Laterally Loaded Piles in Clayey Soils with Sloping Ground. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
87. Rathod D, Muthukkumaran K, Sitharam TG (2017) Behaviour of laterally loaded piles in soft clay on sloping ground. Soil Dyn Soil-Struct Interaction Resilient Infrastruct 1:149–163. https://doi.org/10.1007/978-3-319-63543-9_13
88. Rathod D, Muthukkumaran K, Sitharam TG (2017) Development of non-dimension p–y curves for laterally loaded piles in sloping ground. Indian Geotech J 47(1):47–56
89. Rathod D, Muthukkumaran K, Sitharam TG (2016) Dynamic response of single pile located in soft clay underlay by sand. Int J Geomate 11(26):2563–2567
90. Reiter L (1990) Earthquake hazard analysis: issues and insights (vol 22). Columbia University Press, New York, p 254
91. Dinesh SV, Sitharam TG, Vinod JS (2004) Dynamic properties and liquefaction behaviour of granular materials using discrete element method. Curr Sci 87(10):1379–1387
92. Dinesh SV, Sitharam TG, Hyodo M (2006) DEM simulation of static behavior of granular media and micromechanical analysis under different stress paths. In: Proceedings of the International Symposium on Geomechanics and Geotechnics of Particulate Media, Ube, Japan, 12–14 September 2006
93. Samui P, Sitharam TG (2011) Determination of liquefaction susceptibility of soil based on field test and artificial intelligence. Int J Earth Sci Eng 4(2):216–222
94. Seed HB, Idriss IM (1971) Simplified procedure for evaluating soil liquefaction potential. J Soil Mech FDN 97:1249–1273
95. Sil A, Sitharam TG (2013) Site response evaluation of Agartala City using geophysical and geotechnical data. Int J Geotech Earthq Eng (IJGEE) 4(2):53–73
96. Sil A, Sitharam TG, Sreevalsa K (2013) Probabilistic seismic hazard analysis of Tripura and Mizoram states. Nat Hazards 68(2):1089–1108
97. Sil A, Sitharam TG, Haider ST (2015) Probabilistic models for forecasting earthquakes in the northeast region of India. Bull Seismol Soc Am 105(6):2910–2927
98. Sitharam TG (2009) Seismic microzonation: a tool for disaster mitigation planning. Disaster Advances 2(3): 3–4
99. Sitharam TG (2008) Special issue on: Seismic Microzonation Preface, pp 647–647
100. Sitharam TG, Kumar A, Anbazhagan P (2013) Comprehensive seismic microzonation of Lucknow city with detailed geotechnical and deep site response studies. In: Proceedings of Indian geotechnical conference
101. Sitharam TG, Anbazhagan P, Govinda Raju L (2006) Seismic Response of Soils a case study of Site Specific Ground Response Analysis. Indian Geotechnical Conference, vol 14
102. Sitharam TG, Hegde A (2017) Probabilistic seismic slope stability analyses of rock fill tailing dams: a case study. Proceedings of the 19th international conference on soil mechanics and geotechnical engineering, Seoul
103. Sitharam TG, Amarnath MH (2019) A case study of probabilistic seismic slope stability analysis of rock fill tailing dam. Int J Geotech Earthq Eng (IJGEE) 10(1):43–60

104. Sitharam TG, Arjun S (2014) Comprehensive seismic hazard assessment of Tripura and Mizoram states. J Earth Syst Sci 123(4):837–857
105. Sitharam TG, Vinod JS (2015) Nepal earthquake of April 25, 2015
106. Sitharam TG, Vipin KS (2010) Evaluation of peak ground acceleration and response spectra considering the local site effects: a probabilistic logic tree approach. Int J Geotech Earthq Eng (IJGEE) 1(1):25–41
107. Sitharam TG, Vipin KS (2011) Evaluation of spatial variation of peak horizontal acceleration and spectral acceleration for south India: a probabilistic approach. Nat Hazards 59(2):639
108. Sitharam TG, Vipin KS (2010) Liquefaction potential evaluation based on site classes–a performance based approach. In: International Conferences on recent advances in geotechnical earthquake engineering and soil dynamics. San Diego, California
109. Sitharam TG, Vipin KS (2009) Seismic Soil Liquefaction Based on In situ Test Data. IGC, Guntur, India, Indian Geotechnical Society GEOTIDE, pp 857–864
110. Sitharam TG, Govindaraju L (2004) Geotechnical aspects and ground response studies in Bhuj earthquake, India. Geotech Geol Eng 22(3):439–455
111. Sitharam TG, Anbazhagan P (2012) Microzonation of earthquake hazard: Indian experiences. In: Proceedings of international conference on advances in architecture and civil engineering (AARCV 2012), vol 21
112. Sitharam TG, Anbazhagan P (2007) Seismic hazard analysis for the Bangalore region. Nat Hazards 40(2):261–278
113. Sitharam TG, Anbazhagan P (2008) Seismic microzonation: principles, practices and experiments. EJGE Spec Vol Bouquet 8:61
114. Sitharam TG, Kolathayar S (2012) Probabilistic Evaluation of Seismic Hazard in India: Comparison of Different Methodologies. 15WCEE, Lisboa
115. Sitharam TG, Kolathayar S (2013) Seismic hazard analysis of India using areal sources. J Asian Earth Sci 62:647–653
116. Sitharam TG, Kolathayar S (2018) Preparing for earthquakes: lessons for India. Springer, Berlin
117. Sitharam TG, Srinivasa Murthy BR, Aravind K (2001) A postmortem of the collapse of structures in Ahmedabad during the Bhuj earthquake. In: Proceedings of Indian Geotech. Conference
118. Sitharam TG, Ravishankar BV, Jayan SV (2008) Liquefaction and pore water pressure generation in sand—a cyclic strain approach. J Earthq Tsunami 2(3):227–240
119. Sitharam TG et al (2012) A study on seismicity and seismic hazard for Karnataka State. J Earth Syst Sci 121(2):475–490
120. Sitharam TG et al (2003) Frequency response analysis of layered ground in Ahmedabad during Bhuj earthquake
121. Sitharam TG et al (2005) Seismic hazard studies using geotechnical borehole data and GIS. Proceedings of symposium on seismic hazard analysis and microzonation
122. Sitharam TG, Vipin KS, James N (2011) Evaluation of dynamic properties, local site effects and design ground motions: recent advances. Proceedings of the Post-SMiRT conference seminar on advances in seismic design of structures, systems and components of nuclear facilities. 2011
123. Sitharam TG, Vipin KS, James N (2018) Recent advances in soil dynamics relevant to geotechnical earthquake engineering: advances in Indian earthquake engineering and seismology. Springer, Cham, pp 203–228
124. Sitharam TG, Govindaraju L, Srinivasa Murthy BR (2004) Evaluation of liquefaction potential and dynamic properties of silty sand using cyclic triaxial testing. Geotech Test J 27(5):423–429
125. Sitharam TG, James N, Vipin KS (2010) Seismic hazard map for the state of Karnataka with local site effects: deterministic seismic hazard analysis
126. Sitharam TG, James N, Kolathayar S (2018) Local site effects for seismic zonation: comprehensive seismic zonation schemes for regions at different scales. Springer, Cham, pp 75–108
127. Sitharam TG, James N, Kolathayar S (2018) Principles and practices of seismic zonation: comprehensive seismic zonation schemes for regions at different scales. Springer, Cham, pp 147–166
128. Sitharam TG, James N, Kolathayar S (2018) Comprehensive seismic zonation schemes for regions at different scales. Springer, Berlin
129. Sitharam TG, Anbazhagan P, Mahesh GU (2007) 3-D subsurface modelling and preliminary liquefaction hazard mapping of bangalore city using SPT data and GIS. Indian Geotech J 37(3):210–226
130. Sitharam TG, Anbazhagan P, Ganesha Raj K (2006) Deterministic seismic hazard analysis and estimation of PHA for Bangalore City. International conference on Earthquake Engineering. 2006
131. Sitharam TG, Anbazhagan P, Ganesha Raj K (2006) Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore. Na Hazards Earth Syst Sci Copernicus Publ 6(6):927–939
132. Sitharam TG, Anbazhagan P, Vipin KS (2010) Principles and practices of seismic microzonation: case studies in India. In: International conferences on recent advances in geotechnical earthquake engineering and soil dynamics. San Diego, California. May 2010
133. Sitharam TG, Anbazhagan P, Kumar NJN (2008) Seismic Hazard and microzonation studies using geographic information system-a case study of Bangalore city. KGUG Newsletter
134. Sitharam TG, Kolathayar S, Vipin KS (2010) Evaluation of seismic hazards for India: Deterministic approach including local site effects. Indian Geotechnical Conference—2010, GEOtrendz December 16–18, 2010 IGS Mumbai Chapter and IIT Bombay
135. Sitharam TG, Kolathayar S, James N (2015) Probabilistic assessment of surface level seismic hazard in India using topographic gradient as a proxy for site condition. Geosci Front 6(6):847–859
136. Sitharam TG, Anbazhagan P (2007) Seismic hazard analysis with site effects for Bangalore. In: 13th Asian Regional Conference on Soil Mech. and Geotechnical Engg, 2007, Kolkata
137. Sitharam TG, Anbazhagan P (2008) Seismic Microzonation of Bangalore—Preliminary Maps. In: Indo-Japan Theme Meeting and Workshop (IJTM-2008) on Disaster Risk Reduction, Bangalore
138. Sitharam TG, Raj GK, Vipin KS, Anbazhagan P (2008) Seismic hazard parameters for south India based on probabilistic seismic hazard analysis. In: Proceedings of 24th annual inhouse symposium on space science and technology, January 2008, Bangalore
139. Sonmez H (2003) Modification of the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area (Inegol-Turkey). Environ Geol 44(7):862–871
140. Sreevalsa K (2013) Comprehensive seismic hazard analysis of India. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
141. Srinivas M, Verma AK, Kumar H, Sitharam TG (2020) Stabilization of highly jointed rock mass slopes of the world's highest railway bridge across the deep Gorges of Chenab River
142. Sitharam TG, Dinesh SV (2003) Numerical simulation of liquefaction behaviour of granular materials using discrete element

method. Proc Indian Acad Sci (Earth Planet Sci) 112(3):479–484
143. Sitharam TG, Dinesh SV, Shimizu N (2001) Phase Transformation behaviour in Granular Materials using DEM. Powders and Grains 2001, Kishino ed
144. Sitharam TG, James N, Nayak M (2015) Seismic site characterization and ground response analysis for an offshore site. Jpn Geotech Soc Spec Publ 3(2):1–6
145. Thallak GS, Dinesh SV, Shimizu N (2002) Micromechanical modelling of monotonic drained and undrained shear behaviour of granular media using three dimensional DEM. Int J Numer Anal Meth Geomech 26:1167–1189
146. Vinod JS (2006) Liquefaction and dynamic properties of granular materials: a discrete element approach. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
147. Vipin KS, Sitharam TG (2013) Delineation of seismic source zones based on seismicity parameters and probabilistic evaluation of seismic hazard using logic tree approach. J Earth Syst Sci 122(3):661–676
148. Vipin KS, Sitharam TG (2009) Evaluation of liquefaction return period for Bangalore based on standard penetration test data: performance based approach. Am J Eng Appl Sci 2(3):537–543
149. Vipin KS, Sitharam TG (2011) Multiple source and attenuation relationships for evaluation of deterministic seismic hazard: Logic tree approach considering local site effects. Georisk Assessm Manag Risk Eng Syst Geohazards 5(3):173–185
150. Vipin KS, Anbazhagan P, Sitharam TG (2009) Estimation of peak ground acceleration and spectral acceleration for South India with local site effects: probabilistic approach. Nat Hazards Earth Syst Sci 9(3):865
151. Vipin KS, Sitharam TG, Sreevalsa K (2011) Probabilistic Assessment of Liquefaction Potential for The State of Gujarat. In: Proceedings of Indian geotechnical conference, December 15–17, 2011, Kochi
152. Vipin KS, Sitharam TG, Anbazhagan P (2010) Probabilistic evaluation of seismic soil liquefaction potential based on SPT data. Nat Hazards 53(3):547–560
153. Vipin KS, Sitharam TG, Kolathayar S (2013) Assessment of seismic hazard and liquefaction potential of Gujarat based on probabilistic approaches. Nat Hazards 65(2):1179–1195
154. Vipin K, Sitharam T (2011) Evaluation of liquefaction return period based on local site classes: performance based logic tree approach. Int J Geotech Eng 5(3):245–254
155. Vipin KS, Anbazhagan P, Sitharam TG (2008) Identification of Liquefaction Susceptible Areas in Bangalore using Probabilistic approach Based on SPT data. In: Indian Geotechnical Conference, IGC- 2008, Bangalore
156. Vivek P (2019) Behaviour of granular materials under shock and blast loading. PhD Thesis, Department of Civil Engineering, IISc, Bangalore
157. Vivek P, Sitharam TG (2020) Granular materials under shock and blast loading. Springer, Singapore
158. Wyss M (2017) Four loss estimates for the Gorkha M:78 earthquake, April 25, 2015, before and after it occurred. Nat Hazards 86(1):141–150
159. Kanth SR, Iyengar RN (2007) Estimation of seismic spectral acceleration in peninsular India. J Earth Syst Sci 116(3):199–214
160. Kaklamanos J, Boore DM, Thompson EM, Campbell KW (2010) Implementation of the Next Generation Attenuation (NGA) ground-motion prediction equations in Fortran and R. US Geological Survey Open-File Report, 1296
161. Campbell KW, Bozorgnia Y (2014) NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. Earthquake Spectra 30(3):1087–1115
162. Idriss IM (2014) An NGA-West2 empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. Earthq Spectra 30(3):1155–1177

Prof. T. G. Sitharam is currently the Director of the Indian Institute of Technology, Guwahati. He was a Professor and a Chair professor in the area of Energy and Mechanical Sciences at the Department of Civil Engineering, Indian Institute of Science, Bangalore, India. He is the founder Chairman of the Centre for Infrastructure, Sustainable Transport and Urban Planning (CiSTUP) at IISc, Bengaluru. Presently, he is the Honorary Professorial Fellow at University of Wollongong, Wollongong, Australia, from 2019 to 2022 and Distinguished professor at Hankou University International Innovation Centre, China. Presently, He is the Chairman, Research Council, CSIR-Central Building Research Institute (CBRI), Roorkee. He is the chairman, Executive council of Visvesvaraya Industrial & Technological Museum, Bangalore, India. He is governing council member of National council for Science Museums (NCSM), Govt. of India, and EC member of AICTE, Govt. of India, New Delhi. He is the founder President of International Association for Coastal Reservoir Research (IACRR), registered in NSW, Australia. He is the President, Indian Society for Earthquake Technology (ISET), Roorkee. He is presently the Chairman, AICTE South-western Zonal Committee, Regional office at Bengaluru. Formerly, he was a visiting professor at Dalhousie University, Canada; Yamaguchi University, Japan; Indian School of Mines (IIT-ISM), Dhanbad; and William Mong fellow at University of Hongkong, Hongkong. He was the Vice-president of Indian Society for Earthquake Technology (ISET) and Vice-president of Indian Society of Earthquake Science (ISES). He obtained his bachelors in civil engineering from Mysore University, India, masters in civil engineering from Indian Institute of Science, India (1986), and Ph.D. in Civil Engineering from University of Waterloo, Waterloo, Ontario, Canada (1991). Further, he served as a Research Scientist (for his post-doctoral work) at centre for earth sciences and engineering in the Department of Petroleum Engineering, University of Texas at Austin, Texas, USA, until 1994. He served as a lecturer for six months in 1991 at University of Waterloo, Ontario, Canada. Over the last 35 years, he has carried out research and development extensively in the area of geotechnical and infrastructure engineering and has developed innovative technologies in the area of fracturing and geotechnical applications, leading to about 500 technical papers, 12 books with an H-index of 38 and I-10 index 101with more than 4375 citations. He has 5 patents, more than 120 consulting projects and 2 start-up companies to his credit. He is responsible for designing, restoration and expansion of several earth dams for raw water ponds, tailing ponds, ash ponds and red mud ponds across India. He has guided 30 Ph.D. students at IISc and 30 masters students and trained several postdoctoral and several thousand industry professionals and teachers through continuing education workshops. Presently, he has another 9 Ph.D. students at IISc, Bangalore. He is the chief editor of international journal of Geotechnical Earthquake Engineering, (IJGEE), PA, USA. He is the Editor-in-chief, Springer Transactions in Civil and Environmental Engg series, Book Series, Singapore. He is also fellow of many societies and actively engaged in socially relevant projects.

He has received many awards and credits, including IGS Kuckleman Award, Prof. Gopal Ranjan research award from IIT Roorkee,

IISc Amulya and Vimala Reddy Lecture Award, Sir C.V. Raman State Award for Young Scientists from the Government of Karnataka, S.P. Research award (SAARC) from SP research foundation, USA, and several best paper awards in recognition of his exceptional contributions to Geotechnical Engineering and Engineering Sciences. He has delivered the IGS annual lecture during IGC 2020, organized by IGS Visakhapatnam Chapter.

He is the fellow of Institution of Civil engineers, UK, Fellow of American Society of Civil Engineers, Professional Engineer (P. Eng.), 2019, Chartered Engineer (C. Eng.), 2019, Fellow Institution of Engineers (India), and many other societies.