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Multi-criteria seismic hazard evaluation for Bangalore city, India

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ABSTRACT

Different seismic hazard components pertaining to Bangalore city, namely soil overburden thickness, effective shear-wave velocity, factor of safety against liquefaction potential, peak ground acceleration at the seismic bedrock, site response in terms of amplification factor, and the predominant frequency, has been individually evaluated. The overburden thickness distribution, predominantly in the range of 5–10 m in the city, has been estimated through a sub-surface model from geotechnical bore-log data. The effective shear-wave velocity distribution, established through Multi-channel Analysis of Surface Wave (MASW) survey and subsequent data interpretation through dispersion analysis, exhibits site class D (180–360 m/s), site class C (360–760 m/s), and site class B (760–1500 m/s) in compliance to the National Earthquake Hazard Reduction Program (NEHRP) nomenclature. The peak ground acceleration has been estimated through deterministic approach, based on the maximum credible earthquake of $M_W = 5.1$ assumed to be nucleating from the closest active seismic source (Mandya–Channapatna–Bangalore Lineament). The 1-D site response factor, computed at each borehole through geotechnical analysis across the study region, is seen to be ranging from around amplification of one to as high as four times. Correspondingly, the predominant frequency estimated from the Fourier spectrum is found to be predominantly in range of 3.5–5.0 Hz. The soil liquefaction hazard assessment has been estimated in terms of factor of safety against liquefaction potential using standard penetration test data and the underlying soil properties that indicates 90% of the study region to be non-liquefiable. The spatial distributions of the different hazard entities are placed on a GIS platform and subsequently, integrated through analytical hierarchal process. The accomplished deterministic hazard map shows high hazard coverage in the western areas. The microzonation, thus, achieved is envisaged as a first-cut assessment of the site specific hazard in laying out a framework for higher order seismic microzonation as well as a useful decision support tool in overall land-use planning, and hazard management.

1. Introduction

Seismic hazard, in a broad perspective, refers to any kind of phenomena related to earthquakes capable of imparting potential damages to the built and social environment. Although it is generally defined as a specified level of ground shaking, several other hazard entities such as landslides, liquefaction, tsunamis, seiches are often associated. The hazard is significantly controlled by changes in geotechnical material properties during the earthquake. In fact, site-specific attributes related to surface geologic conditions can induce considerable alterations of the seismic motions (Aki, 1988; Field et al., 1992; Nath et al., 2000; Sitharam and Anbazhagan, 2008). It is, therefore, important to deliver appropriate site-specific design ground motions for earthquake resistant structural design and the hazard appraisal. In cognizance to the existence of multiple hazard components, an appropriate decision support tool for hazard classification would incorporate of every aspect according to their likely contribution to the overall hazard. To that effect, seismic microzonation has been carried out through multi-criteria evaluation technique that accounts for several factors such as site response, shear-wave velocity, landslide, geomorphological features, besides the peak ground accelerations (Sitharam and Anbazhagan, 2008; Pal et al., 2008; Nath et al., 2008). Making improvements on the conventional regional hazard maps, microzonation of a region predicts the hazard to much smaller scales (TC4-ISSMGE, 1999; Sitharam and Anbazhagan, 2008). It involves subdivision of a region into individual areas having different potentials for hazardous earthquake effects, defining their specific seismic behavior for engineering design, and land-use planning (Anbazhagan and Sitharam, 2008b). The seismic microzonation maps are generally envisaged to provide an effective tool

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for land-use planning, hazard mitigation and management, and structural engineering applications, especially in vulnerable zones characterized with rapid urbanization and burgeoning population.

Bangalore metropolis area located at 12°58′N, 77°36′ covering an area of about 220 km^{2,} has been investigated for various seismic hazard components, namely peak ground acceleration at bedrock level, site response, liquefaction potential, effective shear-wave velocity, predominant frequency, and soil overburden thickness. Sitharam and Anbazhagan (2007a) estimated the peak ground acceleration distribution at bedrock level from synthetic ground motions for a controlling seismic source in order to present a deterministic hazard scenario. Sitharam and Anbazhagan (2007b) evaluated site amplification factor, and predominant frequency of soil columns in the region from geotechnical borehole data using SHAKE2000 (Ordonez, 2004). Anbazhagan and Sitharam (2008a) computed the average shear-wave velocity through Multi-channel Analysis of Surface Wave (MASW) surveys at 58 locations across the study region. The velocity measurements were, further, calibrated with those derived from the drilled boreholes data to generate correlations between corrected standard penetration test *N*-values and shear-wave velocity (Anbazhagan and Sitharam, 2009). Sitharam et al. (2007) investigated the overburden soil details, and the soil liquefaction potential in terms of factor of safety against liquefaction in the study region.

In the present study, the different hazard aspects are appraised in order to establish their validity and usefulness, and eventually to provide an amalgamation of the different factors in form of a hazard index map for the study region. The analysis, thus, carried out involved mapping the spatial distribution of these factors on a single reference system (1:20,000 scale resolution) using a Geographical Information System (GIS) platform; each constituting a thematic layer. Following a multi-criteria evaluation technique - analytical hierarchical process (AHP, Saaty, 1980, 1990), each theme and the features have been assigned weights and rankings respectively according to their perceived relative significances to the seismic hazard. The layers are, thereafter, integrated through spatial union to obtain the seismic microzonation map addressing a first-cut assessment of the site specific hazard to layout a framework for higher order seismic microzonation.

2. Study area and regional background

Bangalore city in the southwestern part of India come across as a vulnerable region with its expanding diverse huge population base, and extending urban infrastructure. The city is the principal administrative, industrial, commercial, educational and cultural capital of Karnataka State. It has been the fastest grown city and is presently ranked as fifth biggest city in India. Besides political activities, Bangalore hosts several national scientific laboratories, defense establishments, small and large-scale industries. The city emerged as 'the silicon city of India' with agglomeration of Information Technology corporate establishments, along with influx of thousands of software professionals every year. The metropolis represents a booming commercial venue with expansive infrastructure and diverse population that continues to accommodate the requirement of a modern urban setting. A study concerning the seismological and geotechnical issues towards providing security for the inhabitants and safeguarding the infrastructural investments is, therefore, not only significant but also essential.

Large number of earthquakes with different magnitudes has occurred often in this region (Bansal and Gupta, 1998). Recently, Ganesha Raj and Nijagunappa (2004) highlighted neo-tectonic activities in the Karnataka region and suggested the current seismic zonation of Karnataka placed in lowest hazard zone i.e. zone II of BIS hazard zonation code (BIS, 2002) to be inadequate. The regional environs of the city have been implicated with neo-tectonic and fault reactivation. A seismotectonic map depicting a circular area of about 350 km radius around the city has been depicted in Fig. 1. The active faults and lineaments along with associated seismicity in the region have been examined in following up to the previous studies of Dasgupta et al. (2000), and Ganesha Raj and Nijagunappa (2004). The seismicity is accounted for with a M_W consistent earthquake catalogue covering a period of 200 years from 1807 to 2006. The seismic activities of the relevant faults and implications to the fault-rupture patterns have been discussed in detail by Sitharam et al. (2006). The closest observable lineament extending SW–NE about 105 km with 5.2 km away from the city to the north Mandya–Channapatna–Bangalore Lineament. To the west of Bangalore, amongst several minor faults, Chikmag-

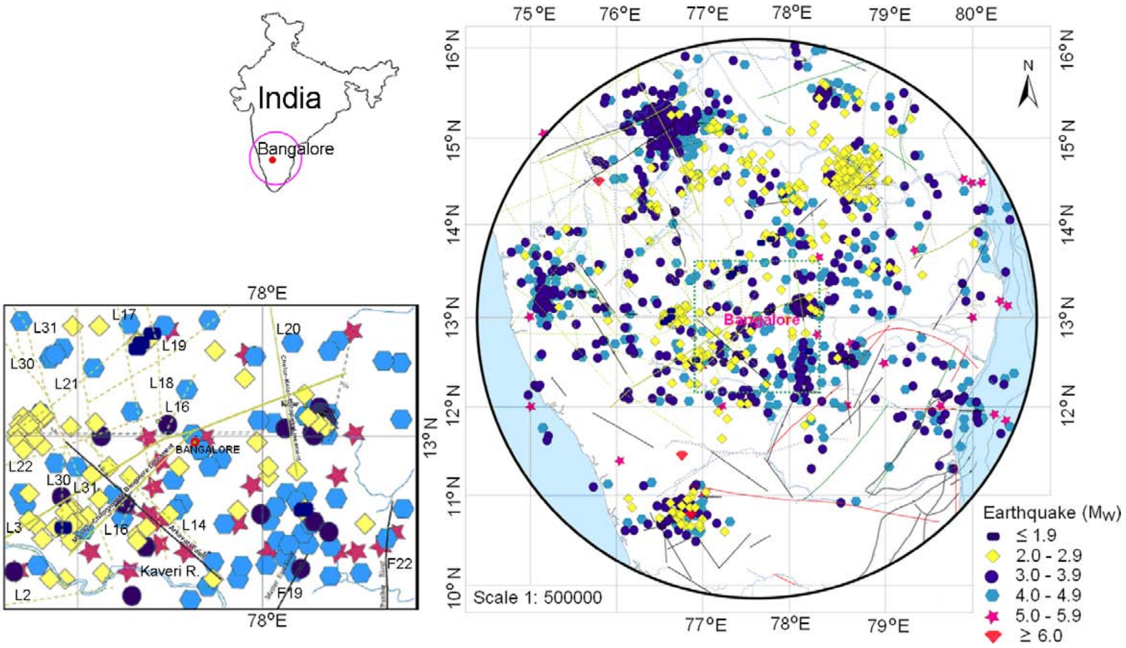

Fig. 1. A seismotectonic map of the study region depicting major linear tectonic features with the seismicity covering a period of 200 years: 1807–2006 (after Sitharam et al., 2006).

alur fault to the north is seen trending in NW–SE orientation (Fig. 1) while Bhavali fault to the south traverses in slight variation from the NW-SE orientation. Southwest from the city, 1900 Coimbatore earthquake of $M_W = 6.2$ occurred near the Bhavani fault that shook the city. In the eastern Dharwar Craton region and closer to Bangalore, Arkavati fault runs in similar trend to the Bhavali fault. Earthquakes of magnitude less than but close to $M_W = 5.0$ have been observed close to Arkavati fault. To the north, the Chitradurga Boundary Fault is seen trending in the N–S direction. A strike-slip mechanism is also indicated in the zone with Bangalore earthquake of March 20, 1984, $M_W = 4.5$ (Rastogi, 1992). On the other hand, to the east, the faults are predominantly oriented in NE–SW fashion. Major faults include Kadiri Fault to the north; Main, Amirdi and Attur faults clustered to the southwest of the zone, and the Cauveri Fault traversing E–W on the southern boundary. Valdiya (1998) highlighted that the seismic activity is generally confined to linear belts related to crosscurrent and terrain-bounding faults, and shear zones implying possible reactivation of the Precambrian faults.

Notably, there were over 150 lakes in and around the city. However, most of them dried up due to soil erosions and encroachments for construction of residential/industrial buildings leaving only 64 at present (Sitharam et al., 2006). The old lakes beds naturally have silty clay and sand that have been filled up with soil over which buildings/structures have been built.

3. Deterministic primary hazard distribution

Earthquakes primarily cause ground shaking that, at times, can be devastating for buildings and subsequently the populace. Seismic hazard analysis, therefore, aims at the assessment of ground motion potential at the site. Amongst several peak ground motion attributes (i.e. peak acceleration, peak velocity and peak displacement), peak ground acceleration (PGA) is often preferred as the hazard quantifier, which represents a short period ground motion parameter signifying damage potential to the buildings thus providing an overall quantitative basis for the design codes and construction practices. However, period-specific spectral acceleration (SA) would also be a better index when specific buildings are considered accounting for applicable resonance frequencies.

The seismic hazard assessment can be either deterministic or probabilistic. The deterministic hazard analysis involves determination of a controlling earthquake referred to as maximum credible earthquake that produces the severest ground motion. The associated strong-motion parameters are estimated accordingly without considering probability of its occurrence. On the other hand, the probabilistic analysis explicitly incorporates quantitative uncertainties in the size, location, rate of recurrence and effects of earthquakes. Both approaches are significant owing to the purpose, the seismic environment, and the scope of the assessment (McGuire, 2001; Anbazhagan et al., 2008). The deterministic approach is appropriate in cases of establishing a seismic framework towards disaster mitigation and management, and long-term earthquake hazard appraisal. Realistic seismic deterministic scenarios are also useful in case of seismic design and retrofits (Nath et al., 2009). However, in the cases where the nature of decision-making is to be based on quantitative information involving uncertainties allowing constrains on investments according to the applicable scheme; for example, structural design requirements, financial planning for earthquake losses (insurance), and investment for urbanization, a probabilistic approach would be more appropriate.

Sitharam and Anbazhagan (2007a) reported a deterministic hazard analysis in the study region. Maximum credible earthquakes corresponding to each tectonic feature have been computed through Wells and Coppersmith (1994) relation between the length of sub-surface fault-rupture and magnitude, by considering possible maximum fault-rupture in each case. The maximum fault-rupture dimensions are, however, constrained by the underlying geology. The fault-rupture lengths, therefore, are construed from the observed seismicity, which indicated the pragmatic maximum fault-rupture (segment) length to be 5% of the total fault length. In order to establish the controlling seismic source, the PGA at the center of the Bangalore city were estimated using the regional attenuation relation of Iyengar and Raghukanth (2004) taking shortest distance from the different sources (faults and lineaments). The highest PGA of 0.159 g has been attributed for a maximum credible earthquake (MCE) of $M_W = 5.1$ at Mandya–Channapatna– Bangalore Lineament, which exceeds more than 50% of PGA due to other sources. The source has been, therefore, considered as the controlling seismic source for the deterministic assessment.

The stochastic simulation algorithm of Boore (1983) has been employed for the strong ground motion synthesis at borehole location points; about 620 bore holes have been dug for geotechnical investigations (discussed in subsequent section) wherefrom the basement depth information has been derived. MCE has been placed at a focal depth of 15 km since larger earthquakes (closer to $M_W = 5.0$) in the source region are observed to be in the depth range. The hypocenter distance from each borehole is taken to be shortest distance from the lineament. The average crustal shear-wave velocity has been taken to be 3.65 km/s. The geometric attenuation G has been taken to be $1/R$ for $R < 100$ km and $1/10\sqrt{R}$ for $R > 100$ km (after Singh et al., 1999), in this R is hypocenter distance in km, the quality factor $Q(f)$ has been taken to be equal to $488\,f^{0.88}$ (Sitharam et al., 2006; Sitharam and Anbazhagan, 2007a), f is the frequency in Hz. A stress drop of 300 bars, and the high-frequency band-limitation parameter, f_{max}, set to 35 Hz has been considered to generate the strong ground motions at 80 Hz as suggested appropriate for 15 km focal-depth earthquakes by Singh et al. (1999) for the Peninsular Indian region. A representative accelerogram has been provided with Fig. 2a. The stochastic simulations employ random vibration theory to predict the peak ground acceleration from time-domain simulations (Boore, 1983). Nevertheless, the number of simulations at closely located sites using the same simulation parameters is not expected to yield highly fluctuating results, which otherwise would indicate huge uncertainty in the method. The uncertainties in the source model and simulation parameters (more appropriate for probabilistic studies) have not been considered for the deterministic analysis (Nath et al., 2009; Anbazhagan et al., 2009)). To avoid minor fluctuations, specific ranges of the predicted PGA values have been zoned through contouring, as depicted in Fig. 2b, which exhibits a monotonic trend with the highest value of 0.15 g to the northwest and lowest of 0.10 g to the southeast.

4. Geotechnical attributes

The strong ground motions caused by an earthquake at a site are greatly influenced by the underlying geotechnical properties of the local soil, implying the necessity to incorporate relevant geotechnical parameters in local specific seismic hazard assessment (Sitharam and Anbazhagan, 2008). Five parameters have been, therefore, considered in the present study: soil overburden thickness, effective shear-wave velocity, predominant frequency, site response, and the factor of safety against liquefaction.

4.1. Soil overburden thickness and effective shear-wave velocity

The bedrock topography of a particular area illustrates the pertinent soil overburden thickness which is an important geological

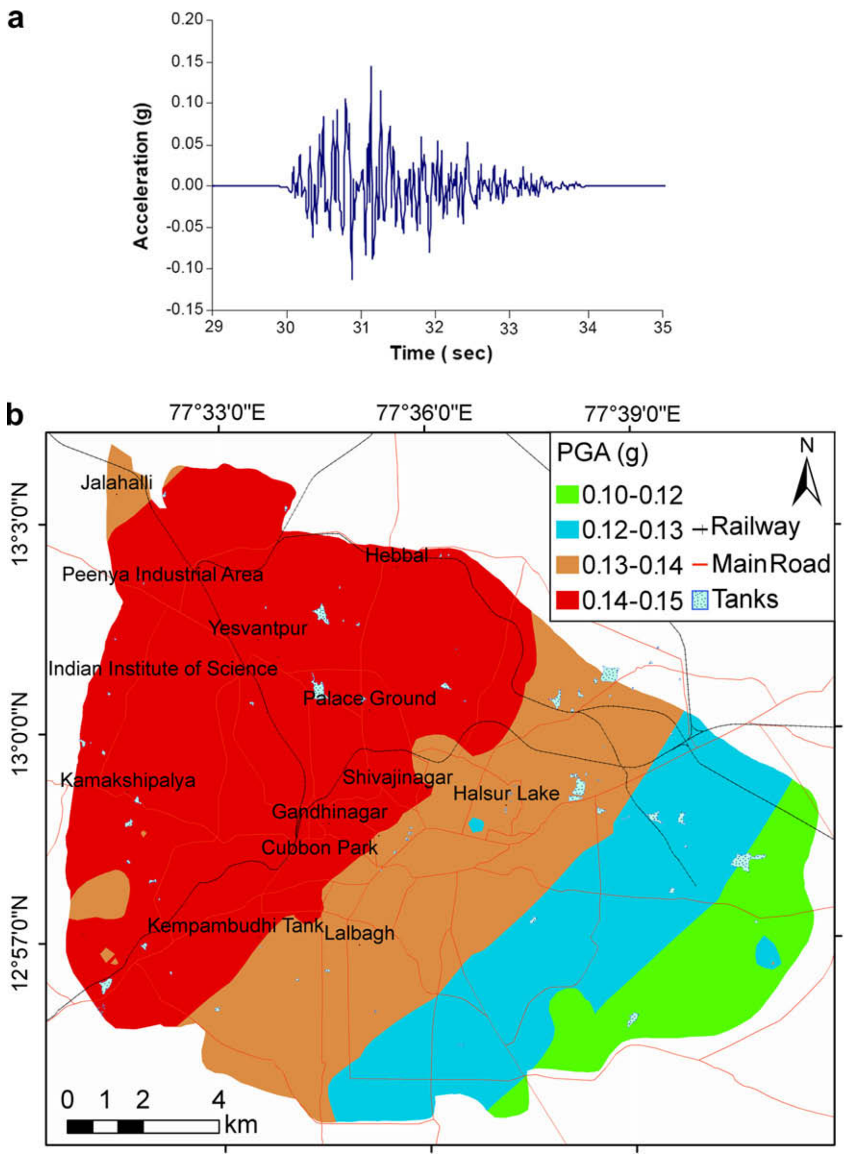

Fig. 2. (a) A representative accelerogram generated through stochastic modeling at bedrock level, and (b) the deterministic spatial distribution of peak ground acceleration at bedrock level depicting a variation from 0.10 to 0.15 g in the Bangalore city.

parameter that significantly contributes to spatial variation of the strong ground motion at the surface due to an earthquake. Sitharam et al. (2007) and Sitharam et al. (2008) developed a sub-surface model of the city using geotechnical bore-log data. A typical bore log in the southern part of the study area is presented in Fig. 3. A general depth-wise distribution of the soil type derived from the bore-log data is given in Table 1. The data from 170 boreholes covering the study region, as depicted in Fig. 4, have been considered to estimate the corresponding soil overburden thickness. The spatial variation of the overburden thickness, obtained through contouring using the estimated values at each borehole, is presented in Fig. 4. It is seen that the overburden thickness in the study region varies from 1 m to 25 m but is predominantly in the range of 5–10 m.

The shear-wave velocity, V_S, distribution in the city has been evaluated through multi-channel analysis of surface wave (MASW) survey and subsequent data analysis by Anbazhagan and Sitharam (2008a). The study covered 58 sites within the 220 sq. km of the urban center. Typical dispersion curve and shear-wave velocity is given in Fig. 5a and b. The recorded data have been selected according to the associated highest signal-to-noise ratio. All tests has been carried out with geophone interval of 1 m, source being kept on both sides of the spread and source to the first and last receiver were also varied from 5 m, 10 m and 15 m to avoid the effects of near-field and far-field. The captured Rayleigh wave has been analyzed using SurfSeis software.

The effective shear-wave velocity, V_H, for the depth, d, of soil has been computed as

$$V_H = \sum d_i \Big/ \sum \left(\frac{d_i}{v_i}\right) \tag{1}$$

where d_i and v_i denote the thickness (in m) and shear-wave velocity in ms^{-1} (at a shear strain level of 10^{-5} or less) of the ith formation or layer respectively, in a total of N layers. Shear-wave velocity averaged over the upper 30 m (V_S^{30}) is accepted for site classification purpose as per National Earthquake Hazards Reduction Program (NEHRP, Building Seismic Safety Council, 2001), and International Building code (IBC) classifications (Dobry et al., 2000; Kanli et al., 2006). Therefore, V_S^{30} is generally considered for amplification and site response studies. However, if the rock is found to be located within a depth of about 30 m, the effective shear-wave velocity of

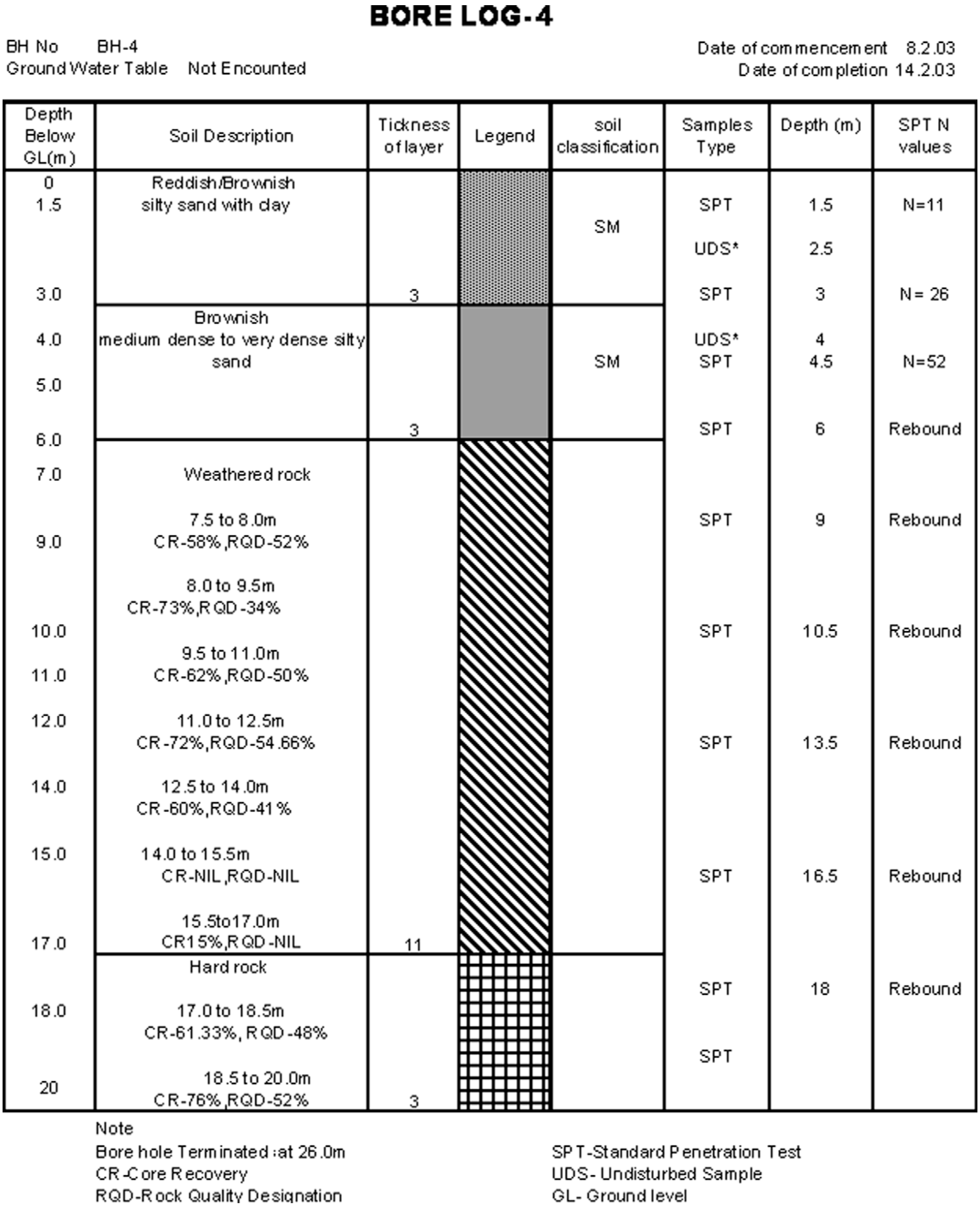

Fig. 3. An example of typical bore log from the study area.

Table 1
General depth-wise distribution of the soil in the study region.

Layer	Northwest	Southwest	Northeast	Southeast
First	Silty sand with clay, 0–3 m	Silty sand with gravel, 0–1.7 m	Clayey sand, 0–1.5 m	Filled up soil, 0–1.5 m
Second	Medium to dense silty sand, 3–6 m	Clayey sand, 1.7–3.5 m	Clayey sand with gravel, 1.5–4 m	Silty clay, 1.5–4.5 m
Third	Weathered rock, 6–17 m	Weathered Rock, 3.5–8.5 m	Silty sand with Gravel, 4–15.5 m	Sandy clay, 4.5–17.5 m
Fourth	Hard rock, below 17 m	Hard rock, below 8.5 m	Weathered rock, 15.5–27.5 m	Weathered rock, 17.5–38.5 m
Fifth	Hard rock	Hard rock	Hard rock, below 27.5 m	Hard rock, below 38.5 m

soil thickness (overburden thickness), rather than V_S^{30}, is considered since the presence of hard rock mass would implicate a higher V_S^{30} (Anbazhagan and Sitharam, 2008c). The soil thicknesses were evaluated from the nearby borehole logs well within 500 m distance. In compliance to the NEHRP nomenclature (Building Seismic Safety Council, 2001), the site classification scheme has been adopted,

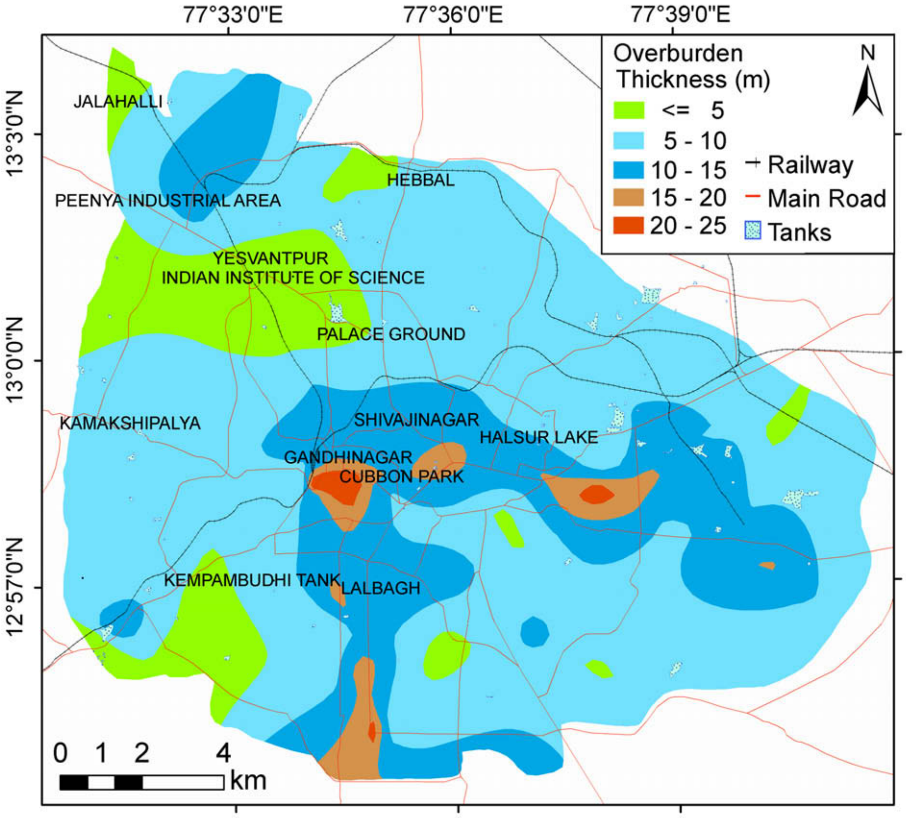

Fig. 4. The spatial distributions of overburden thickness of Bangalore city.

and the map, thus, obtained is depicted in Fig. 6. The ranges of V_S^{30} in the region exhibits site class D (180–360 m/s), site class C (360–760 m/s), and site class B (760–1500 m/s) as per Anbazhagan et al. (2009).

4.2. Site Response and predominant frequency

The study region, predominantly, presents altered soil structures due to dried up water bodies and reclamation of land (Anbazhagan and Sitharam 2009). The pertinent loose and silty soil conditions are prone to ground motion amplification that may be attributed to resonance effects of the velocity contrasts between the unconsolidated overburden and bedrock, apart from rebounding effects within the stratigraphic layers. As seismic waves travel from bedrock to the surface, certain characteristics of the waves, such as amplitude and frequency content is modified as they pass through the soil deposits, which in turn can transfer large accelerations to structures, particularly when the resulting seismic wave frequency matches with the resonant frequencies of the structures. Therefore, high significance is associated to site specific ground response analysis to determine effect of local soil conditions on amplification of seismic waves, and hence the ground response spectra for future design purposes. The response of a soil column is generally seen to be dependent on the frequency of the base motion as well as on the geometry and material properties of the soil layer above the bedrock (Anbazhagan et al., 2009).

Sitharam and Anbazhagan (2007b) performed a detailed ground response analysis in the study region. In this work, the sub-surface model of the study area, represented by 170 geotechnical bore logs and 58 shear-wave velocity profiles, has been employed to account for the soil properties and synthetic ground motions at each borehole locations to compute the associated site effects through one-dimensional ground response with SHAKE2000 computer program (Ordonez, 2004). The program accounts for the non-linear soil behavior by adopting equivalent linear steps using the shear modulus and damping reductions curves. The values for modulus and damping compatible with the effective strains in each geological layer are obtained through an iterative procedure. It is seen from the shear-wave velocity profiles that the hard rock/engineering rock in the region is seen to be ~760 m/s (site class B). The synthetic strong ground motion due to the controlling earthquake of the deterministic hazard analysis (Section 3), therefore, has been given as an input to the hard rock/engineering bedrock having the shear-wave velocity of 760 m/s. Accordingly, the peak acceleration values and acceleration time histories were computed at the top of each sub layer. The site response has been quantified as amplification factor computed as a ratio of the peak horizontal acceleration at the ground surface to the peak horizontal acceleration at the bedrock. The latter is obtained from the synthetic acceleration time history generated at each borehole.

Fig. 7a depicts the distribution of site amplification factor in the study region. The site response distribution indicates predominantly higher site amplification (2–4 times) to the north, and lower site amplification (2 times) dominating most of the region, except for central and a few parts where site amplification is not observed (i.e. 1 times). Noting that the overall soil overburden thickness is rather shallow, the soil distribution that is mostly sand (silty and clayey) is associated with higher site amplification. To that extent, the predominant frequency is also seen high to the north. The site amplification, as the one observed in the central part of the study region, might be due to possible hard rock intrusions at the deeper sub-surface corroborated by the pertinent borehole data, indicative of the geologic history of the area. Overall, the observed site amplification factors in view of the soil conditions and sediment thickness are consistent to those of several previous investigations.

The site predominant frequency is defined as the frequency of seismic response of the soil columns corresponding to the maxi-

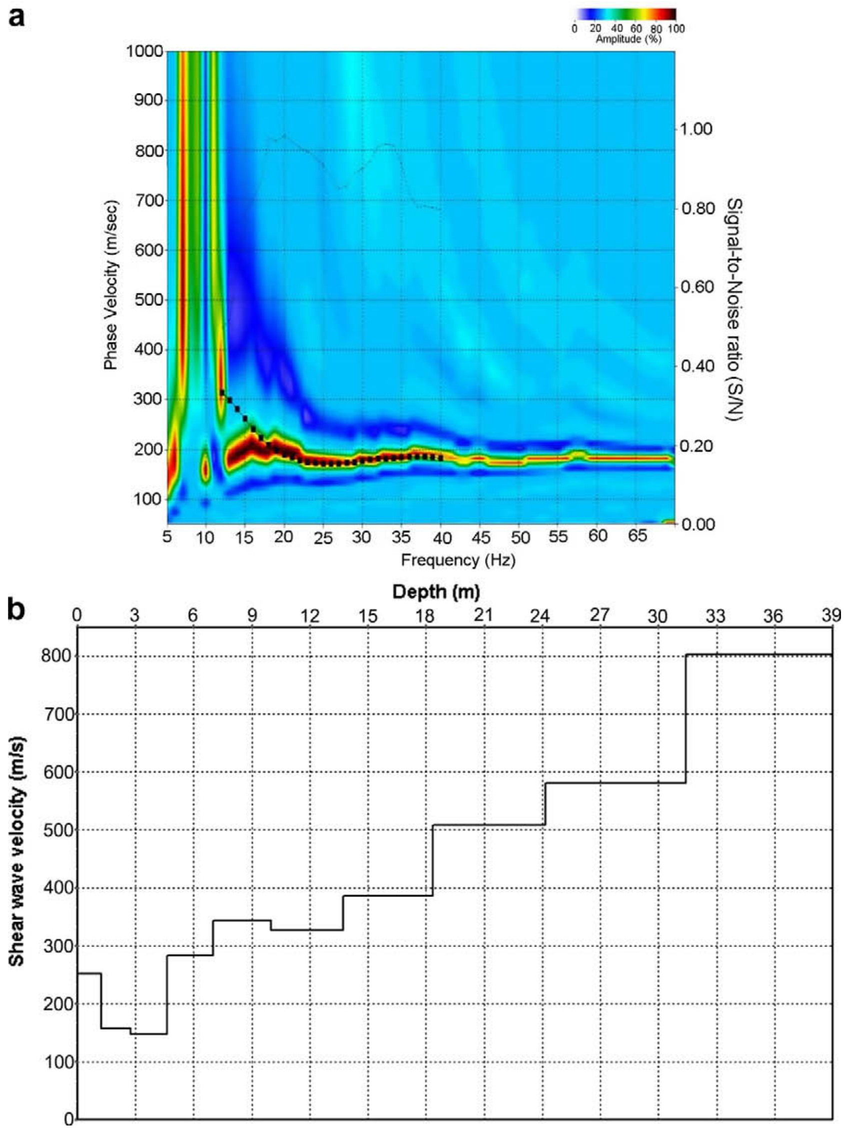

Fig. 5. Typical results from multi-channel analysis of surface wave (MASW) survey for the study area: (a) dispersion curve and (b) shear-wave velocity profile.

mum Fourier amplitude. It has been widely used to categorize the soil in respect to the ground motion. Sitharam and Anbazhagan (2007b) estimated the predominant frequency distribution in the Bangalore city from the Fourier spectrum computed using SHAKE2000 at 170 boreholes sites. The predicted values have been contoured and presented as a distribution map as depicted in Fig. 7b. The predicted predominant frequency distribution is seen to be predominantly in range of 3.5–9.5 Hz in the study region, while higher values are observed to the north of the region. Major part of the study area (Bangalore) have buildings with single to 3–4 stories, which are prone to higher frequency (2–10 Hz) and these values are within the predominant frequency distribution of the soil in the study region.

4.3. Factor of safety against liquefaction

Soil liquefaction occurs when loose saturated unconsolidated soils transform from a solid state to liquefied state due to increasing pore water pressures, and thus decreasing effective stress, induced by their tendency to decrease in volume under drained conditions when subjected to earthquake loading. Moderate to major earthquakes can cause liquefaction hazard. The hazard has been seen more prone in loose to moderate granular soils with poor drainage, such as silty sands or sands and gravels capped or containing seams of impermeable sediments (Youd and Idriss, 2001). The attributing factors include the grain size distribution of soil, duration of earthquake, amplitude and frequency of shaking, distance from epicenter, location of water table, cohesion and permeability of the soil.

In the study region, the liquefaction hazard assessment has been carried out by Sitharam et al. (2007) using standard penetration test (SPT) data and the underlying soil properties. The liquefaction susceptibility is a measure of an inherent resistance of soil to liquefaction, and can range from non susceptible, regardless of seismic loading, to highly susceptible, which means that very little seismic energy is required to induce liquefaction. Liquefaction susceptibility is evaluated based on the primary relevant soil properties such as grain size, fine content, and density, degree of saturation, SPT-*N* values and age of the soil deposit in each of the bore logs. To that effect, the empirical assessment is decided on basis that the soil is susceptible for liquefaction if (i) presence of sand layers at depths less than 20 m, (ii) encountered water table depth less than 10 m, and (iii) SPT '*N*' values indicating blow counts less than 20.

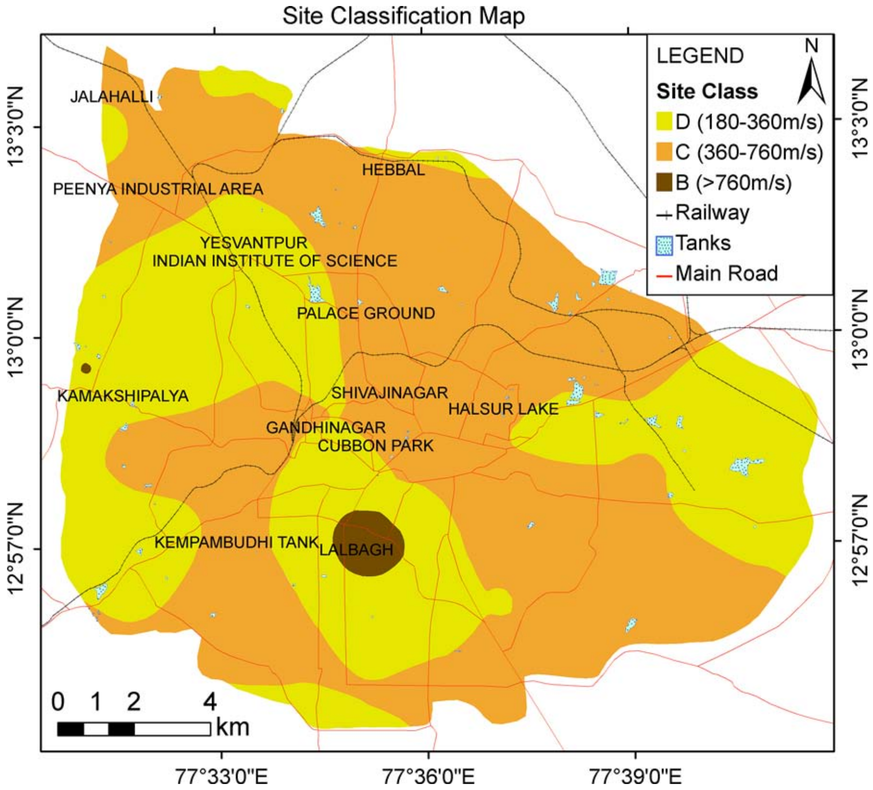

Fig. 6. NEHRP site classification map of Bangalore city (modified after Anbazhagan et al., 2009).

About 620 borehole data have been used to evaluate factor of safety against liquefaction in the terrain. The factor of safety against liquefaction (FSL) of soil layers have been evaluated based on the simplified procedure of Seed and Idriss (1971) and subsequent revisions of Seed et al. (1983), Youd et al. (2001), and Cetin et al. (2004). To evaluate FSL, the earthquake induced loading is expressed in terms of cyclic shear stress and compared to the liquefaction resistance of the soil. The former is represented by Cyclic Stress Ratio (CSR) while the latter by Cyclic Resistance Ratio (CRR). The surface consistent peak ground acceleration corresponding to the MCE is used to estimate the cyclic stress ratio (CSR). In the cyclic stress approach the pore pressure generation is related to the cyclic shear stress, hence the earthquake loading is represented in terms of cyclic shear stresses. Liquefaction resistance of soil depends on how close the in situ state of soil is to the state corresponding to failure, which have been assessed in situ test based on SPT '*N*' values. Cyclic resistance ratio (CRR) has been derived on corrected *N* value. The MCE of M_W = of 5.1 necessitates a magnitude scaling factor (MSF, Seed and Idriss, 1982) to be evaluated as given below,

$$\mathrm{MSF} = \left[\frac{10^{2.24}}{M_W^{2.56}}\right] \tag{2}$$

The cyclic stress ratio caused by the earthquake is greater than the cyclic resistance ratio of in situ soil then liquefaction could occur. FSL, is computed as follows,

$$\mathrm{FSL} = \left[\frac{\mathrm{CRR}_{7.5}}{\mathrm{CSR}}\right]\mathrm{MSF} \tag{3}$$

The factor of safety for each layer of soil was arrived by considering corresponding "$(N_1)_{60cs}$" values to arrive CRR and CSR for earthquake loading. The minimum factor of safety from each bore logs has been considered to represent the factor of safety against liquefaction. Eventually, the FSL distribution for the city, which is depicted in Fig. 8, have been mapped taking into account both the empirical and geotechnical assessments. The reclaimed sites of old lakes compiled through newspaper publications, accounts of the inhabitants, and old toposheets in a study conducted by Indian Institute of Science, Bangalore has been indicated in the figure. It is seen that a reclaimed site, namely Kurubarahalli Lake, in the northeast of the study region exhibited high susceptibility to the hazard, although most of the reclaimed sites do not. Only 4.2% of the total area are seen to have FSL <1 whereas about 14.7% have FSL between 1 and 2. About 12.5% have FSL between 2 and 3, and about 68% have FSL >3. About 33% of the locations have silty clay soil that may cause stress reduction in soil during earthquake as they posses liquid limit >33 and plasticity index >12. The bore logs at the locations having FSL <1 indicate that very loose silty sand with clay and sand is present up to a depth of about 6 m which are classified as medium to fine sand with very low field SPT-*N* values. Shallow water tables (~1.2 m depth) are also found in these locations. These factors may be attributed for the low factor of safety. About 90% of the area in the study region have higher factor of safety and are non-liquefiable. The city is, therefore, safe from liquefaction hazard except at few locations where the overburden is sandy silt complemented by shallow water table, notwithstanding that there has been no account of liquefaction in the area.

5. Seismic microzonation

Multi-criteria assessment for hazard delineation leading to seismic microzonation has been accomplished previously in other Indian regions – Guwahati City (Nath et al., 2007, 2008), Sikkim Himalaya (Pal et al., 2008), and Delhi (Mohanty et al., 2007). The hazard mapping is achieved through multi-criteria based decision support tool formulated by Saaty (1980) referred to as Analytical

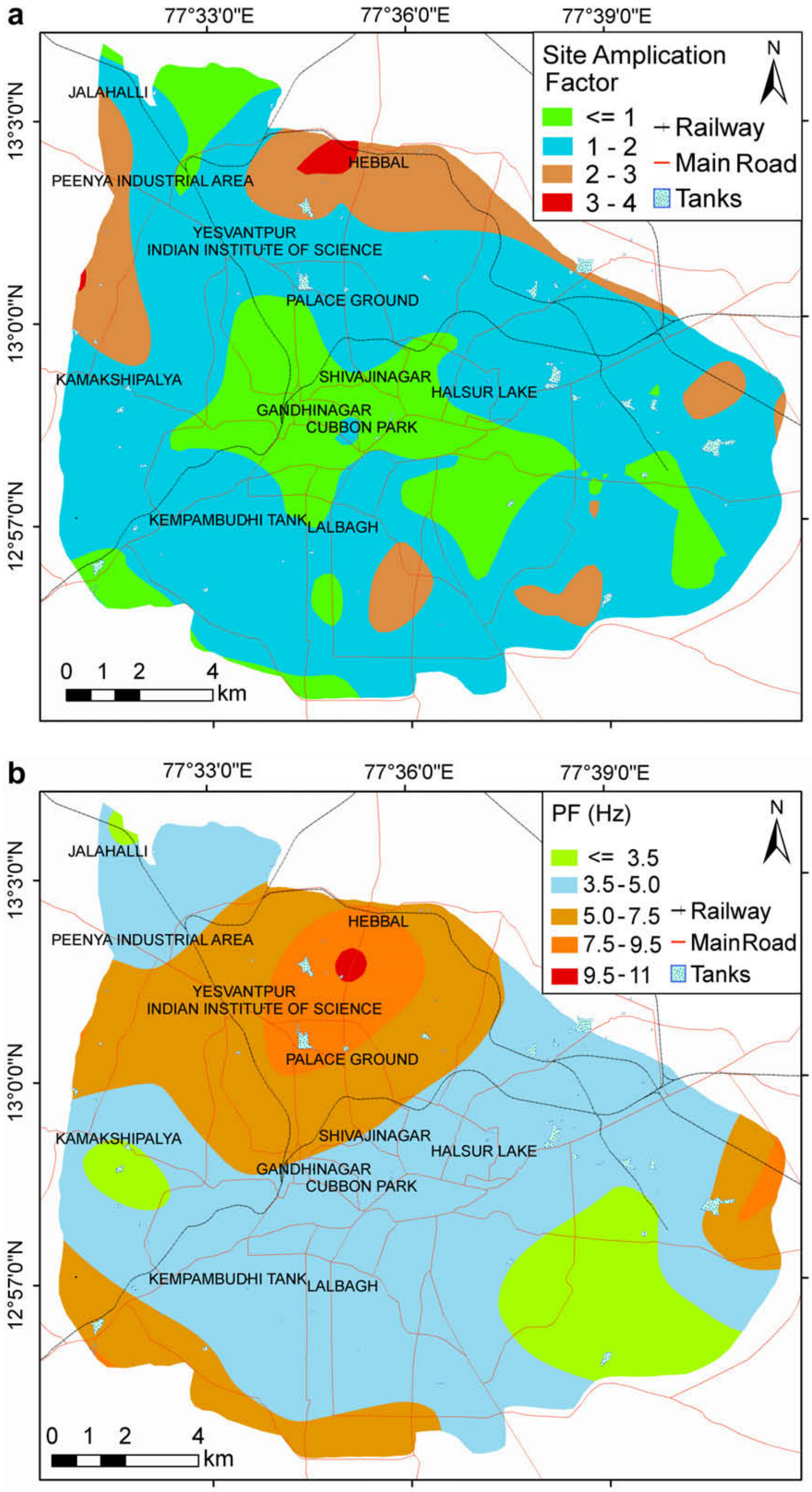

Fig. 7. The maps of Bangalore metropolis area depicting (a) site amplification, and (b) predominant frequency (PF) distribution respectively.

Hierarchal Process (AHP). The tool uses hierarchical structures to represent a problem, and thereafter, develop priorities for the alternatives based on the consensus judgment. The technique utilizes organized priority in terms of weights assigned to each criteria or themes, which could be easily incorporated to the thematic layers on a GIS platform. The weighting activities in multi-criteria decision-making are effectively dealt with hierarchical structuring and pair-wise comparisons wherein the judgment between two particular elements is formulated rather than prioritize an entire list of elements. The process involves construction of a matrix of pair-wise comparisons (ratios) between the factors of adopted parameters depicting relative importance based on the assigned weightage. For example, six parameters are scaled as 1–6 on basis of the relative importance over one another such that 1 indicating

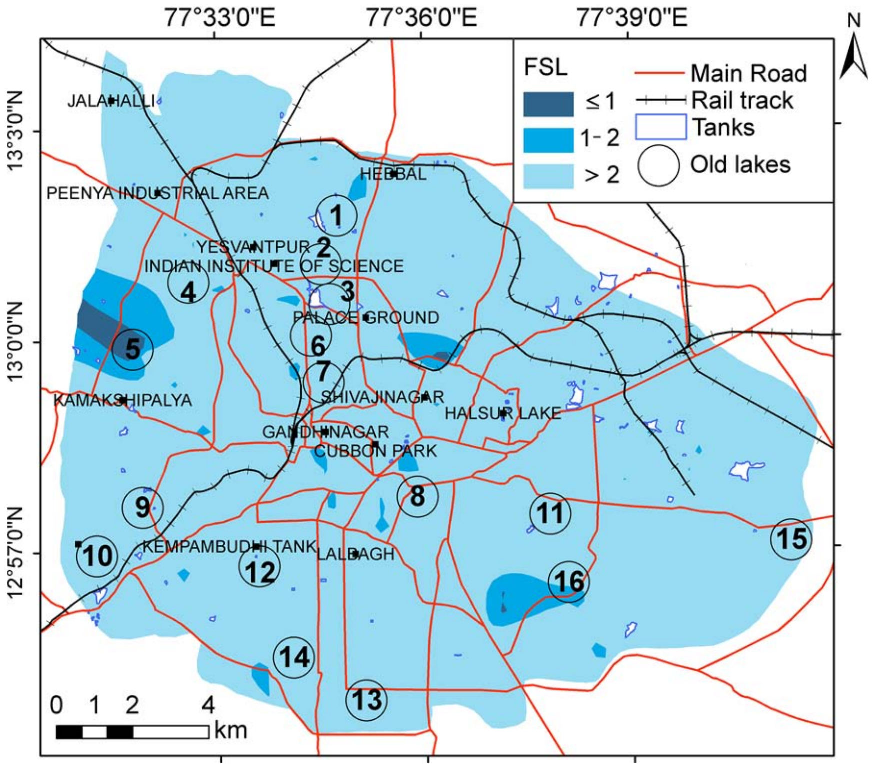

Fig. 8. The liquefaction hazard in the Bangalore city is characterized by the factor of safety against liquefaction. The site of old lakes (reclaimed land) are indicated with circles with index: (1) Tumkur Lake, (2) Ramshetty Palya kere, (3) Oddarapalaya Lake, (4) Ketamaranahalli Lake, (5) Kurubarahalli Lake, (6) Agasana Lake, (7) Jakkarayana kere, (8) Dharmambudhi Lake, (9) Vijayanagar Chord Rd. Lake, (10) Marenahallli Lake, (11) Sampangi Lake, (12) Kalasipalya Lake, (13) Siddapura Lake, (14) Tyagarajanagar Lake, (15) Domlur Lake, and (16) Shule Lake. The existing lakes are referred to as tanks.

that the two factors are of equal importance, and 6 representing that one factor is more important than the other, and correspondingly reciprocals of the scale (i.e., 1/1–1/6) show that one is less important than others. The allocation of weights for the parameter or the theme depends on the relative importance of factors decided through consensus opinion of participatory group of decision makers. Accordingly, normalized weights are derived in each case. Within each theme, the values varies significantly and are hence classified into various ranges or types collectively referred to as feature of a thematic layer. The associated features are ranked or scored within the theme. The initial integral ranking, $R_{i,}$ is normalized to ensure that no layer exerts an influence beyond its determined weight using the following relation,

$$R_{norm} = (R_i - R_{min})/(R_{max} - R_{min}) \tag{4}$$

where R_{norm}, R_{min} and R_{max} denotes the normalized, assigned minimum and maximum ranks respectively. In the present study, GIS software – ArcGIS 9.0 has been used for the purpose of thematic mapping through vector layer generation, and the spatial analysis. The advantage of GIS is the capability to store, manipulate, analyze as well as display spatial and attribute data. The GIS framework also allows one to account for added levels of details and complexity, apart from facilitating easy querying.

The hazard themes, pertaining to the study region materialized as thematic layers on the GIS platform in the present analysis, are: (i) soil overburden thickness (SOT), (ii) effective shear-wave velocity (ESV), (iii) factor of safety against liquefaction potential (FSL), (iv) peak ground acceleration (PGA) at seismic bedrock, (v) site response in terms of Amplification factor (SA), and (vi) predominant frequency (PF). Each thematic layer has been georeferenced on Universal Transverse Mercator coordinate system. The corresponding weights and the ranks to each thematic layer and the feature ranks thereof are assigned accordingly to the apparent contribution of the layers to the overall seismic hazard. The geological site conditions greatly influences the strong ground motion at a site and hence, higher importance is given to those attributes directly connected to geological and geotechnical site conditions (DST, 2007, Sitharam and Anbazhagan, 2008). The basement topography represented by SOT arbitrarily controls the site specific hazard, especially in the cognizance to the contrast in geophysical properties between the basement and the soil deposits in the study region, and hence has been accorded the highest weightage. The sediment thickness implicates rebounding of the seismic waves leading to site amplifications, and therefore, the ranks are decided according to the increasing order of the thickness (or basement depth) i.e. higher the depth, higher the rank. The next attribute is the site class that is defined on basis of effective shear-wave velocity. The soil liquefaction potential, evaluated in terms of FSL, is known to be a determinant urban geotechnical hazard, especially at the reclaimed sites previously of natural water bodies, and

Table 2
Pair-wise comparison matrix of themes and their normalized weights.

Themes	SOT	SC	FSL	PGA	SA	PF	Normalized weights
SOT	6/6	6/5	6/4	6/3	6/2	6/1	0.2857
SC	5/6	5/5	5/4	5/3	5/2	5/1	0.2381
FSL	4/6	4/5	4/4	4/3	4/2	4/1	0.1905
PGA	3/6	3/5	3/4	3/3	3/2	3/1	0.1429
SA	2/6	2/5	2/4	2/3	2/2	2/1	0.0952
PF	1/6	1/5	1/4	1/3	1/2	1/1	0.0476

SOT: soil overburden thickness; SC: site classification; FSL: factor of safety against liquefaction potential; PGA: peak ground acceleration at the seismic bedrock; SR: site response in terms of maximum amplification factor; PF: predominant frequency.

Table 3
Normalized weights and ranks assigned to the respective themes and the features thereof for the thematic integration.

Themes	Weight	Feature	Rank	Normalized Rank
SOT (m)	0.2857	>20	5	1.00
		15–20	4	0.75
		10–15	3	0.50
		5–10	2	0.25
		⩽5.0	1	0.00
SC	0.2381	Site class D	3	1.00
		Site class C	2	0.50
		Site class B	1	0.00
FSL	0.1905	<1	3	1.00
		1–2	2	0.50
		>2	1	0.00
DPGA (g)	0.1429	>0.15	5	1.00
		0.14–0.15	4	0.75
		0.13–0.14	3	0.5
		0.12–0.13	2	0.25
		⩽0.120	1	0.00
SA	0.0952	>4	4	1.00
		3– ⩽ 4	3	0.66
		2– ⩽ 3	2	0.33
		1– ⩽ 2	1	0.00
PF (Hz)	0.0476	⩽3.5	5	1.00
		3.5– ⩽ 5.0	4	0.75
		5– ⩽ 7.5	3	0.50
		7.5– ⩽ 9.5	2	0.25
		9.5– ⩽ 11	1	0.00

swampy tracts. The attribute is strongly connected to the loose soil conditions and is, therefore, accorded with the appropriate weightage. Next in the order is PGA that constitutes the deterministic hazard conforming to the basement. The 1-D site amplification factor (SA) distribution essentially computed from the shear-wave velocity profiles over the engineering bedrock comprises a factor that adds up to the peak ground acceleration. Finally, PF is incorporated to address a generic hazard conditions for the building distribution. The building distribution in the study region comprises mostly of 3–4 stories reinforced concrete structures that are generally prone to high frequencies (2–10 Hz); well within the observed predominant frequency range of the soil columns in the terrain (3–9.5 Hz). A generic scheme to address the overall higher raised buildings is, therefore, adopted in the present analysis with lower predominant frequency being assigned higher ranking in order to facilitate an elementary hazard appraisal. The present framework, thus, accounts for the overall hazard considering the basin effect (soil overburden thickness, predominant frequency), soil effect (site classification, site response, liquefaction potential), and the effect of the projected deterministic ground motion (peak ground acceleration). Table 2 presents the pair-wise comparison matrix for the respective themes and their normalized weights. The normalized ranks assigned to the features of each theme are listed in Table 3. The thematic integration is achieved through the following equation,

$$DHI = (SOT_W \cdot SOT_R + SC_W \cdot SC_R + FSL_W \cdot FSL_R + SOT_W.SOT_R + ESV_W \cdot ESV_R + DPGA_W \cdot DPGA_R + SA_W \cdot SA_R + PF_W \cdot PF_R)/\sum W \quad (5)$$

where DHI represents the deterministic hazard index, and the subscripts – W and R have been assigned accordingly to indicate weight and ranking respectively.

The deterministic seismic microzonation map, achieved in the present analysis, is depicted in Fig. 9. The variations of DHI could be grouped into four classifications representing negligible, low, moderate, and high zones.

6. Discussion and conclusions

The present study focuses on delivering a seismic framework to enable decision on further investigations, especially, higher order

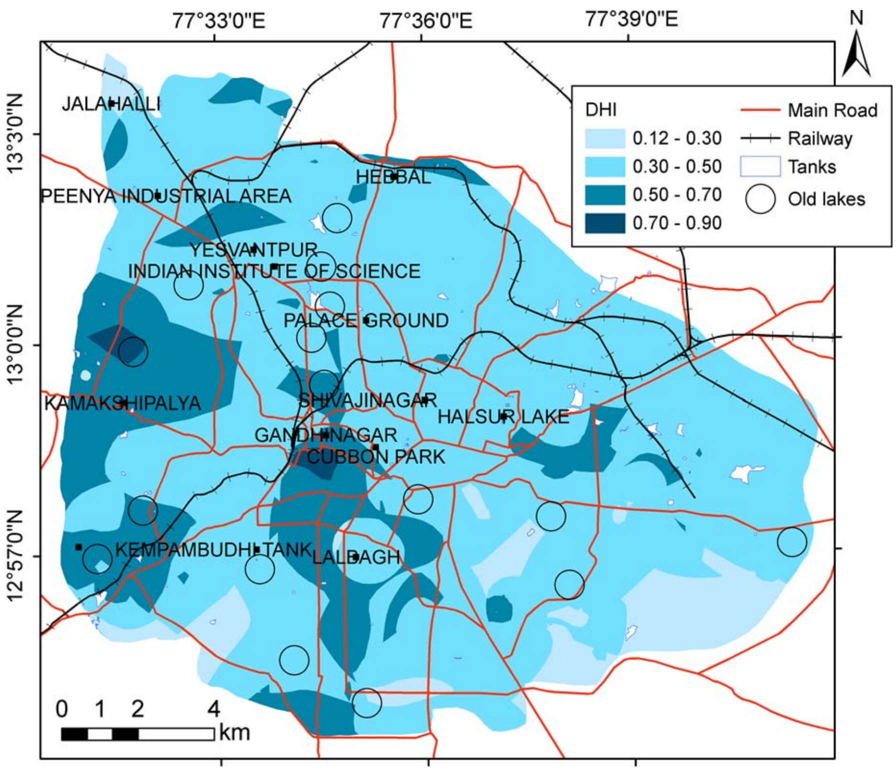

Fig. 9. The deterministic seismic hazard microzonation map of Bangalore city; the listing of old lakes (reclaimed lands) have been given in caption of Fig. 8.

ward-specific analysis. This calls for a deterministic assessment, which usually preludes a probabilistic one. The study region is located in low seismicity zone. However, deadly earthquakes such as M_W = 6.2 Latur 1993, M_W = 5.8 Jabalpur 1997, and M_W = 7.6 Gujarat 2001 have occurred in the seismotectonic regime that encompasses the peninsular India. The high uncertainty involved in assessment of the hazard predicates the significance of a deterministic approach in the present study. A singular and dominant scenario has been assumed in the hazard projection that outstrips those anticipated from other regional faults. Furthermore, higher priority in the thematic integration process has been assigned to the geotechnical themes, emphasizing more on the local geotechnical hazard variations.

The final seismic hazard microzonation map obtained in the present analysis indicates that low hazard zone occupies most parts of the city. It is also seen that negligible hazard zones in a few pockets of the southeast and southwest parts of the Bangalore city conform to the sites of site class C. Interestingly, zones of site class B in the region is seen with low hazard likely due to the emphasized overburden thickness. It is seen that zones of low to moderate hazard encompass almost all the sites of old lakes (reclaimed land) as well as existing ones with most of the reclaimed lands in the northern parts under moderate hazard. High hazard conforming to that of liquefaction susceptibility is seen in the area west of the study region. However, very shallow basement depths ($\sim$5 m) is a likely cause that all the areas having factor of safety against liquefaction (FSL) less than or equal to one do not come under high hazard in the final hazard map. The patches of maximum hazard are seen at the central region, which can be attributed to the overburden thickness.

The present analysis accomplishes a groundwork assessment of the site specific hazard laying out a framework for higher order seismic microzonation (1:5000). Period specific analyses based on spectral accelerations and non-linear site response analysis are also envisage for the future studies to address building typological ward-wise distribution in the city.

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References

Aki, K., 1988. Local Site Effects on Strong Ground Motion. Earthquake Engineering and Soil Dynamics II – Recent Advances in Ground Motion Evaluation, June 27–30, Park City, Utah.
Anbazhagan, P., Sitharam, T.G., 2009. Spatial variability of the weathered and engineering bed rock using multichannel analysis of surface wave survey. Pure and Applied Geophysics 166 (3), 409–428.
Anbazhagan, P., Sitharam, T.G., 2008a. Mapping of average shear wave velocity for Bangalore region: a case study. Journal of Environmental and Engineering Geophysics 13 (2), 69–84.
Anbazhagan, P., Sitharam, T.G., 2008b. Seismic microzonation of Bangalore. Journal of Earth System Science 117 (S2), 833–852.
Anbazhagan, P., Sitharam, T.G., 2008c. Site characterization and site response studies using shear wave velocity. Journal of Seismology and Earthquake Engineering 10 (2), 53–67.
Anbazhagan, P., Sitharam, T.G., Vipin, K.S., 2009. Site classification and estimation of surface level seismic hazard using geophysical data and probabilistic approach. Journal of Applied Geophysics 68 (2), 219–230.
Anbazhagan, P., Vinod, J.S., Sitharam, T.G., 2008. Probabilistic seismic hazard analysis for Bangalore. Natural Hazards 48, 145–166.
Bansal, B.K., Gupta, S., 1998. A glance through the seismicity of peninsular India. Journal of the Geological Society of India 52, 67–80.
BIS, 2002. IS1893-2002 (Part 1): Indian Standard Criteria for Earthquake Resistant Design of Structure Part 1– Resistant Provisions and Buildings, Bureau of Indian Standards, New Delhi.
Boore, D.M., 1983. Stochastic simulation of high frequency ground motions based on seismological models of the radiated spectra. Bulletin of the Seismological Society of America 73, 1865–1894.
Building Seismic Safety Council, 2001. NEHRP recommended provisions for seismic regulations for new buildings and other structures. In: 2000 Ed., Part 1: Provisions, Prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency (Report FEMA 368), Washington, DC.
Cetin, K.O., Seed, R.B., Kiureghian, A.D., Tokimatsu, K., Harder Jr., L.F., Kayen, R.E., Moss, R.E.S., 2004. Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. Journal of Geotechnical and Geoenvironmental Engineering 12, 1314–1340.
Dasgupta, S., Pande, P., Ganguly, D., Iqbal, Z., Sanyal, K., Venaktraman, N.V., Dasgupta, S., Sural, B., Harendranath, L., Mazumadar, K., Sanyal, S., Roy, A., Das, L.K., Misra, P.S., Gupta, H., 2000. Seismotectonic Atlas of India and its Environs, Geological Survey of India, Calcutta, India.
Dobry, R., Borcherdt, R.D., Crouse, C.B., Idriss, I.M., Joyner, W.B., Martin, G.R., Power, M.S., Rinne, E.E., Seed, R.B., 2000. New site coefficients and site classification system used in recent building seismic code provisions. Earthquake Spectra 16, 41–67.
DST, 2007. Seismic microzonation atlas of Guwahati region, Seismology Division, Department of Science & Technology, Govt. of India, New Delhi.
Field, E.H., Jacob, K.H., Hough, S.E., 1992. Earthquake site response estimation: a weak motion case study. Bulletin of the Seismological Society of America 82, 2283–2307.
Ganesha Raj, K., Nijagunappa, R., 2004. Major lineaments of Karnataka State and their relation to seismicity: remote sensing based analysis. Journal of the Geological Society of India 63, 430–439.
Iyengar, R.N., Raghukanth, S.T.G., 2004. Attenuation of strong ground motion in peninsular India. Seismological Research Letter 75, 530–540.
Kanli, A.I., Tildy, P., Pronay, Z., Pinar, A., Hemann, L., 2006. Vs30 mapping and soil classification for seismic site effect evaluation in Dinar region, SW Turkey. Geophysical Journal International 165, 223–235.
McGuire, R.K., 2001. Deterministic vs. probabilistic earthquake hazard and risks. Soil Dynamics and Earthquake Engineering 21, 377–384.
Mohanty, W.K., Walling, M.Y., Nath, S.K., Pal, I., 2007. First order seismic microzonation of Delhi, India using geographic information system (GIS). Natural Hazard 40, 245–260.
Nath, S.K., Thingbaijam, K.K.S., Raj, A., 2008. Earthquake hazard in the Northeast India - A seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city. Journal of Earth System Science 117, 809–831.
Nath, S.K., Sengupta, P., Sengupta, S., Chakrabarti, A., 2000. Site response estimation using strong motion network: a step towards microzonation of Sikkim Himalayas seismology. Current Science 79, 1316–1326.
Nath, S.K., Raj, A., Thingbaijam, K.K.S., Kumar, A., 2009. Ground motion synthesis and seismic scenario in Guwahati City – a stochastic approach. Seismological Research Letters 80 (2), 233–242.
Nath, S.K., Thingbaijam, K.K.S., Raj, A., Shukla, K., Pal, I., Nandy, D.R., Yadav, M.K, Bansal, B.K., Dasgupta, S., Majumdar, K., Kayal, J.R., Shukla, A.K., Deb, S.K., Pathak, J., Hazarika, P.J., Paul, D.K., 2007. Seismic scenario of Guwahati City. In: Proceedings of the International Workshop on Earthquake Hazard and Mitigations, 7–8 December, pp. 210–218.
Ordonez, G.A., 2004. SHAKE2000 A Computer Program for the 1D Analysis of Geotechnical Earthquake Engineering Problems. User's Manual, 306pp.
Pal, I., Nath, S.K., Shukla, K., Pal, D.K., Raj, A., Thingbaijam, K.K.S., Bansal, B.K., 2008. Earthquake hazard zonation of Sikkim Himalaya using a GIS platform. Natural Hazards 45, 333–377.
Rastogi, B.K., 1992. Seismotectonics inferred from earthquakes and Earthquake sequences in India during the 1980s. Current Science 62, 101–108.
Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, NY.
Saaty, T.L., 1990. Multicriteria Decision Making: The Analytic Hierarchy Process. RWS Publications, Pittsburgh, PA.
Seed, H.B., Idriss, I.M., 1971. Simplified procedure for evaluating soil liquefaction potential. Journal of Soil Mechanics and Foundation Division, American Society of Civil Engineers 97, 1249–1274.
Seed, H.B., Idriss, I.M., Arango, I., 1983. Evaluation of liquefaction potential using field performance data. Journal Geotechnical Engineering 109, 458–482.
Seed, H.B., Idriss, I.M., 1982. Ground Motions and Soil Liquefaction During Earthquakes, Monogr. 5. Earthquake Engineering Research Institute, University of California, Berkeley.
Singh, S.K., Ordaz, M., Dattatrayam, R.S., Gupta, H.K., 1999. A spectral analysis of the 21 May 1997, Jabalpur, India, earthquake (M_W = 5.8) and estimation of ground motion from future earthquakes in the Indian shield region. Bulletin of the Seismological Society of America 89 (6), 1620–1630.
Sitharam, T.G., Anbazhagan, P., 2007a. Seismic hazard analysis for Bangalore region. Natural Hazard 40, 261–278.
Sitharam, T.G., Anbazhagan, P., 2007b. Seismic microzonation of Bangalore. In: Proceeding of Workshop on Microzonation. Indian Institute of Science, Bangalore, pp. 44–75.
Sitharam, T.G., Anbazhagan, P., Ganesha Raj, K., 2006. Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore. Natural Hazards Earth System Science 6, 927–939.

Sitharam, T.G., Anbazhagan, P., Mahesh, G.U., 2007. Liquefaction hazard mapping using SPT data. Indian Geotechnical Journal 37 (3), 210–226.

Sitharam, T.G., Samui, Pijush., Anbazhagan, P., 2008. Spatial variability of rock depth in Bangalore using geostatistical neural network and support vector machine models. Journal of Geotechnical and Geological Engineering 26, 503–517.

Sitharam, T.G., Anbazhagan, P., 2008. Seismic Microzonation: Principles, Practices and Experiments. EJGE Special Volume Bouquet 08, online, p. 61. <http://www.ejge.com/Bouquet08/Preface.htm>.

TC4-ISSMGE, 1999. Manual for Zonation on Seismic Geotechnical Hazard, Revised edition, Technical Committee for Earthquake Geotechnical Engineering (TC4) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), 209p.

Valdiya, K.S., 1998. Late quaternary movements and landscape rejuvenation in south-eastern Karnataka and adjoining Tamil Nadu in southern India shield. Journal of the Geological Society of India 51, 139–166.

Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America 84, 975–1002.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Liam Finn, W.D., Harder Jr., L.H., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Marting, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., Stokoe, K.H.I.I., 2001. Liquefaction resistance of soils: summary from the 1996 NCEER. NCEER/NSF workshops on evaluation of liquefaction resistance of soils. Journal of Geotechnical and Geoenvironmental Engineering 127, 817–833.

Youd, T.L., Idriss, I.M., 2001. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. Journal of Geotechnical and Geoenvironmental Engineering 127, 297–313.