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Seismic hazard assessment – a holistic microzonation approach

S. K. Nath and K. K. S. Thingbaijam

Dept. of Geology and Geophysics, Indian Institute of Technology, Kharagpur, India

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Abstract. The probable mitigation and management issues of seismic hazard necessitate seismic microzonation for hazard and risk assessment at the local level. Such studies are preceded with those at a regional level. A comprehensive framework, therefore, encompasses several phases from information compilations and data recording to analyses and interpretations. The state-of-the-art methodologies involve multi-disciplinary approaches namely geological, seismological, and geotechnical methods delivering multiple perspectives on the prevailing hazard in terms of geology and geomorphology, strong ground motion, site amplification, site classifications, soil liquefaction potential, landslide susceptibility, and predominant frequency. The composite hazard is assessed accounting for all the potential hazard attributing features with relative rankings in a logic tree, fuzzy set or hierarchical concept.

1 Introduction

Socio-economic and environmental impacts are implicit in the scientific and technological aspects towards the mitigation and management of seismic hazards outlining well-defined objectives: (i) evaluation of earthquake and related hazards, (ii) standardization of a global implementation scheme to facilitate uniform action plans towards adapting urbanization regulations and codes for design and constructions practices, and (iii) seismic vulnerability assessment, and risk prognosis to enable preventive measures against the hazard. The seismic hazard defines the potentially damaging ground shaking in terms of peak ground acceleration (PGA), peak ground velocity (PGV), and/or peak ground displacement (PGD). The quantitative assessment can be achieved either through a deterministic or probabilistic approach, the former delivers absolute values, while the latter estimates the same in terms of probability of non-exceedance corresponding to a certain determined level at a site of interest. A quasi-deterministic or quasi-probabilistic approach employs a hybrid seismological, geological, geomorphological, and geo-technically guided framework wherein all the potential hazard attributing features are considered with relative rankings in a logic tree, fuzzy set, or hierarchical concept (Nath, 2005).

Regional hazard zonations do not incorporate local and secondary effects induced by the earthquakes leading to its infeasibility in landuse development and planning, hazard mitigation and management, and structural engineering applications at site-specific terms. It is necessary to overcome these limitations, especially in the highly populated urban centers with unplanned urbanization practices in vogue. Seismic microzonation is, therefore, envisaged to subdivide a region into sub-regions in which different safeguards must be applied to reduce, and/or prevent damages, loss of life and societal disruptions; in case a large devastating earthquake strikes the region. It involves prediction of the hazard at much intrinsic scale with enhanced resolution and greater precision (say, from 1:50 000 to 1:25 000, 1:10 000, or 1:5 000 scales).

A microzonation project extends from elementary to exhaustive data analyses involving innumerous technical aspects underlying the knowledge base with methodological diversity, but culminating ultimately into recommendations defining constraints on the national/global regulations with local ones. A framework that addresses the pertinent technical issues is reported here with an overview of the state-of-the-art practices and methodologies, with illustrated applications in three geologically different regions - hilly terrains of Sikkim Himalayas, Guwahati city overlying a shallow sedimentary basin, and Bangalore city in a flat topography.

Correspondence to: S. K. Nath
(nath@gg.iitkgp.ernet.in)

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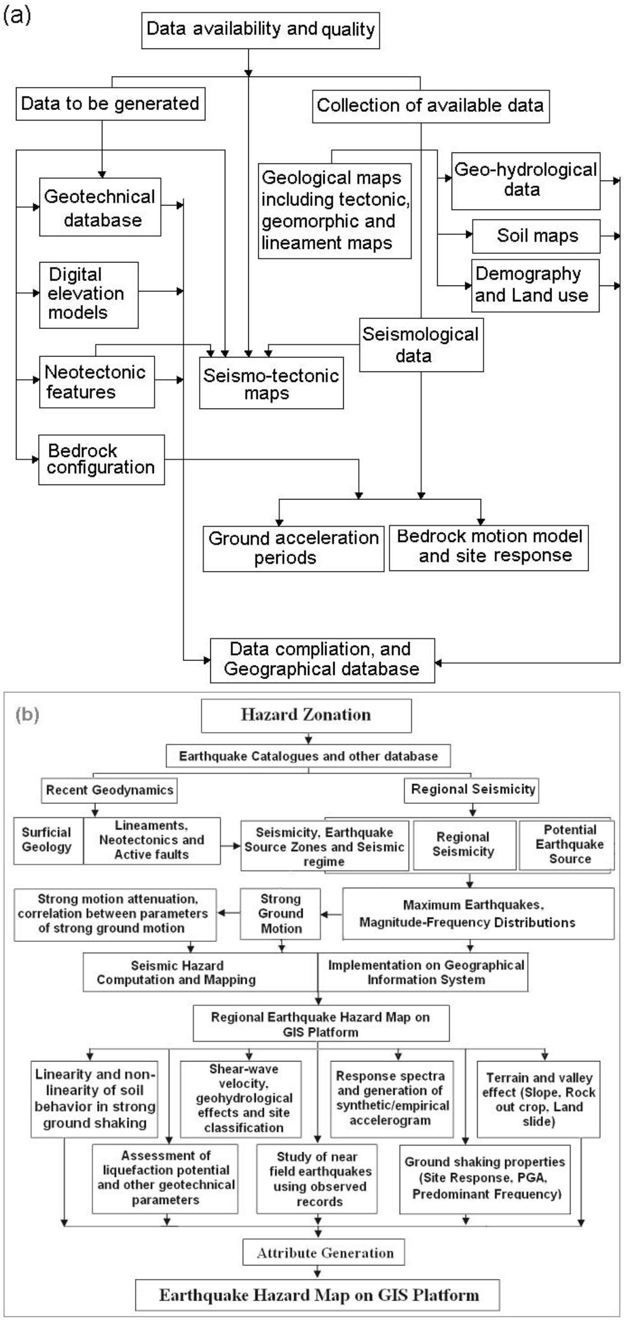

Fig. 1. Overall perspective of a seismic microzonation project: **(a)** data considerations and flow, and **(b)** framework outlining regional to local hazard assessment (after Nath et al., 2008b).

2 Microzonation framework

A seismic microzonation process is initiated with rudimentary assessments based on existing regional level hazard estimation, seismotectonic and macro-seismic studies. Several local specific hazard factors are, thereafter, evaluated and mapped on a Geographical Information System (GIS) platform with a uniform and consistent georeferencing scheme. A broad framework is depicted in Fig. 1. The scheme outlines compilation of information related to seismicity, identification of potential seismic source zones, development of seismicity models, and maximum earthquake prognosis in the regional level supported by earthquake catalogues and other relevant data such as fault database. The local level assessments involve mapping of surficial geological and geomorphological features supported by 2/3 D sub-surface models, and development of geotechnical database, and evaluation of different surficial soil attributes (e.g. density, rigidity, compressibility, damping, water content, etc.), and basement topography. The prevalent seismic characteristics, in terms of predominant frequency, site response, path and source attributes, are generally established through analytical and numerical treatment of the waveform, micro-tremor and geotechnical data, and thereupon, deterministic assessment is carried out by means of strong ground motion simulations. Additional evaluations include that of relevant earthquake induced effects such as soil liquefaction and landslides. Eventually, a composite assessment is taken up of the geological, geotechnical, and seismological attributes to deliver the seismic microzonation in terms of a hazard index map. A microzonation project can be viewed into three levels in order of the mapping resolution, precision, data volume and complexity of the problems (Bard et al., 1995). The elementary level comprises of compilation of available data delivering zonation in the scale of 1:25 000 to 1:10 000. The next level is achieved with specific surveys that include drilling, trenching, geophysical data acquisition, etc with comprehensive analysis/synthesis. The third highest level involves enormous volume of data compilation from a larger number of investigation points, enhanced techniques and exhaustive data processing to deliver the high resolution hazard maps in the scales of 1:10 000 or 1:5 000.

3 Regional assessments

The regional level analysis encompasses the seismicity, seismic sources, and earthquake potential based on available historical and instrumental data covering hundreds of years, micro- and macro-seismicity, regional tectonics and neotectonics (faults/lineaments network), seismotectonics, geology, geo-hydrology, crustal structure, landslides incidents, observed soil liquefactions, etc. (Nath et al., 2008b). Long-term earthquake catalogues are associated with two important issues namely data completeness and magnitude scale inhomogeneity, the former necessitating a temporal segregation of the data according to its completeness (Kijko 2004) while in the latter, empirical relations connecting the different magnitude scales are used to homogenize the magnitude scale to moment magnitude, M_w, owing to its applicability to all magnitude ranges, faulting types, and hypocentral depths of the earthquakes. A large scale seismicity analysis is envisaged to examine spatial patterns (represented by b-value, and fractal correlation dimension of the epicenters or hypocenters), which along with the tectonic background delivers a broad seismic source zonation (e.g. Thingbaijam et al., 2008). Another alternative is seismicity smoothening of Woo (1996) that caters to spatial distribution of event activity rates.

The maximum, characteristics, or maximum credible earthquakes in a region can be estimated from maximum fault-rupture projected on fault/lineament known or otherwise established from paleoseismic investigations (Wells and Coppersmith, 1994; Hanks and Bakun, 2002; Rajendran et al., 2004). Likewise, the estimation may also be derived from the slip deficiency based on the historical events and geodetic studies (Anderson et al., 1996). However, association of unknown fault complexities presents limitations in such deterministic assessments. A general technique employs homogenous earthquake catalogue to derive appropriate seismicity models to establish the annual recurrences. The faults likely to generate major earthquakes can be inferred from observed geological deformation episodes. Large scale micro-seismicity recordings can enable detecting active faults on the geological and geomorphologic signatures.

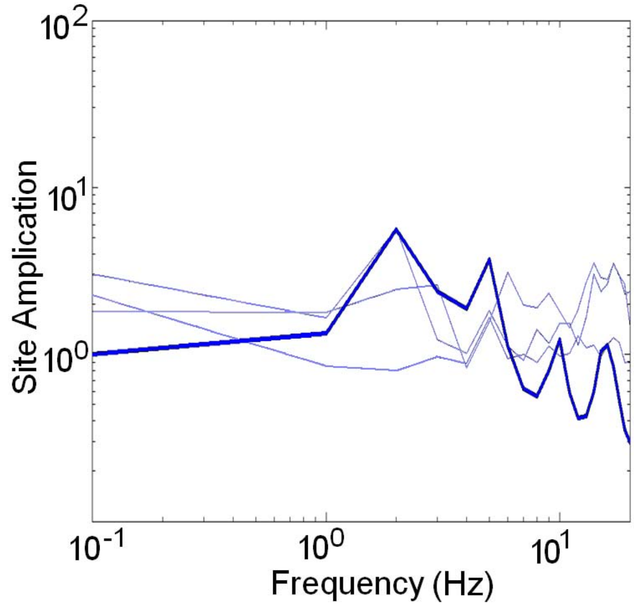

Fig. 2. Site amplification factor versus frequency evaluated through HVSR method from strong motion data (in bold curve) calibrated against those estimated through 1-D geotechnical analysis (in lighter shade curves) at borehole sites located closely to the strong ground motion station (after Nath et al., 2008a).

4 Local specific assessments

4.1 Geology and geomorphology

The geology and geomorphology serves as a significant attribute towards seismic ground motion depiction at a site of interest (Aki, 1988; Panizza, 1991; Hartzell, 1992; Nath et al., 2002a, 2008b). In the geological and geomorphological studies, the near-surface signatures pertaining to the recent sedimentary deposits–alluvium, flood plains, cliffs, slope aspects, etc. can be complemented by borehole litholog, exploratory drill holes, surface elevation model, land-cover, and basement topography derived from vertical electrical resistivity soundings and other geophysical investigations.

4.2 Shear wave velocity

The shear wave velocity profile of soil column is used for site response modeling as well as site classification adhering to National Earthquake Hazard Reduction Program (NEHRP, Building Seismic Safety Council 2001) and Uniform Building Code (UBC, ICBO 1994) terminology. Several techniques are available to obtain sub-surface shear wave velocity profiles that include, (i) using empirical equations between SPT N-values obtained from geotechnical borelog, and the average shear wave velocity (e.g. Fumal and Tinsley, 1985; Imai and Tonouchi, 1982), (ii) multi-channel analysis of surface waves (MSAW, Park et al., 1999), (iii) spectral analysis of surface waves (Stokoe et al., 1994), and (iv) cone penetration test. These techniques are often employed in combination to authenticate and maintain consistency within specified uncertainty in the interpretations of different observations. The spatial mapping is generally done either with the average values for the sediment depth, or 30 m from the surface of the soil column. The latter is widely used for site classification.

4.3 Site response

The site amplification of ground motion is primarily attributed to either the geomorphological features that produce scattering, focusing, or defocusing of incident energy (topographic effect) or thick alluvium-filled terrain that causes reverberations due to trapped energy (basin effect). Techniques used widely to quantify site response in terms of site amplification factors include (i) horizontal-to-vertical spectral ratio, (ii) generalized inversion approach, (iii) standard spectral ratio method with reference to a rock site (iv) coda wave technique, and (v) geotechnical evaluation of the soil transfer function using available software viz. SHAKE, SHAKE2000, WESHAKE, ShakeEdit, etc. (Nath et al., 2002b; Kramer, 1996; Kato et al., 1995; Lermo and Chavez-Garcia, 1993; Hartzell, 1992). The site amplification factor estimated from geotechnical data analysis can complement the ones assessed from strong ground motion waveform. An example of calibration of HVSR site response with those estimated through geotechnical analysis is depicted in Fig. 2. Application of multiple techniques allows resolving ambiguity associated with the estimation. Validations

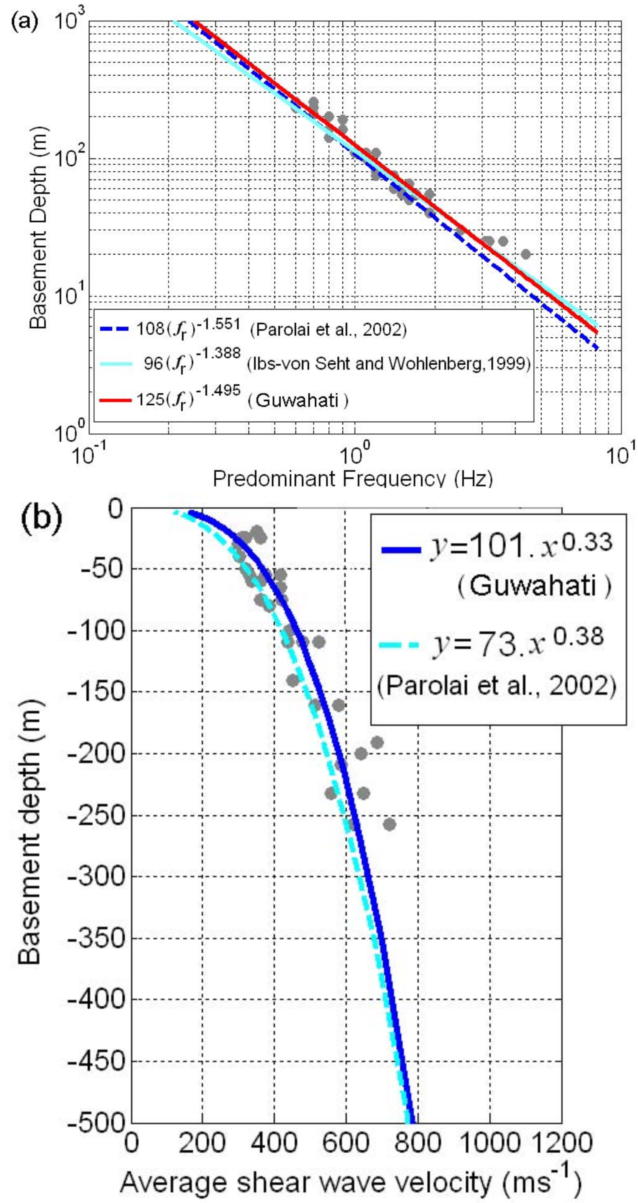

Fig. 3. Local specific relations between average shear wave velocity, and predominant frequency with the basement depth.

can be achieved through macro-seismic intensity distribution for previous/historical earthquakes (e.g. Hough and Bilham, 2008).

4.4 Predominant frequency

The predominant frequency corresponds to the maximum amplitudes of the ground motion in frequency domain. The proximity of predominant frequency of the soil layers and natural frequency of the buildings indicate higher vulnerability of the built-environment owing to resonance effects (Navarro and Oliveiram, 2006). The assessment of predominant frequency distribution in a particular terrain can be performed through waveform data analysis that may be strong ground motion (accelerations), broadband (velocity) or ambient noise (micro-tremors). The Horizontal-to-Vertical Spectral Ratio (HVSR) analysis on ambient noise measurements purposed by Nakamura (1989) offers advantage of easy data acquisition, besides being inexpensive and reliable so far as the basin response effect is considered. Local specific relations between average shear wave velocity and predominant frequency with the basement depth can be established to enable durability in the spatial extrapolation/ interpolation of these parameters (e.g. Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002). Figure 3 depicts such relations observed in Guwahati city.

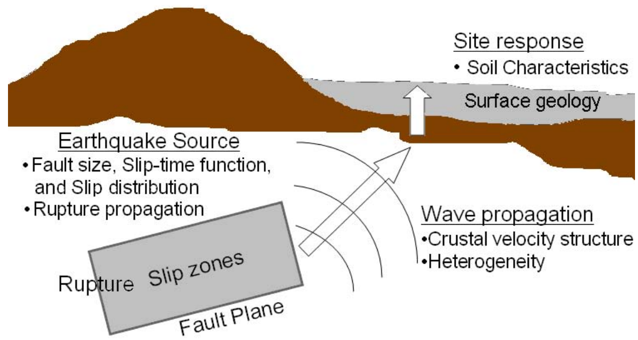

Fig. 4. Strong motion generation process.

4.5 Strong motion synthesis and deterministic seismic hazard

The quantitative assessment of seismic hazard necessitates measurement of peak ground motion parameter (e.g. PGA) from earthquake records. Paucity of strong ground motion data records under conditions similar to design earthquakes in terms of tectonic regime, earthquake size, local geology, and near fault conditions necessitates analytical or numerical approach for a realistic prognosis of the possible seismic effects. The strong ground motion modeling must accommodate: (i) the seismic wave radiation from a fault rupture, (ii) propagation through the crust, and (iii) modifications by the site conditions as depicted in Fig. 4. Several techniques are available that differs in the theoretical considerations, data and computational requirements. Realistic results vis-à-vis complexity and computational as well as data requirement are the deciding factors for applicability of a particular technique. Some of the techniques widely used include: (i) stochastic approach (Boore and Atkinson, 1987; Beresnev and Atkinson, 1997; Motazedian and Atkinson, 2005), (ii) Green functions method (Bouchon and Aki, 1977), (iii) empirical Green functions method (Hartzell, 1978; Irikura, 1983), (iv) finite difference method (Panza, 1985; Oprsal and Zahradnik, 2002), (v) finite element method (Frankel, 1989),

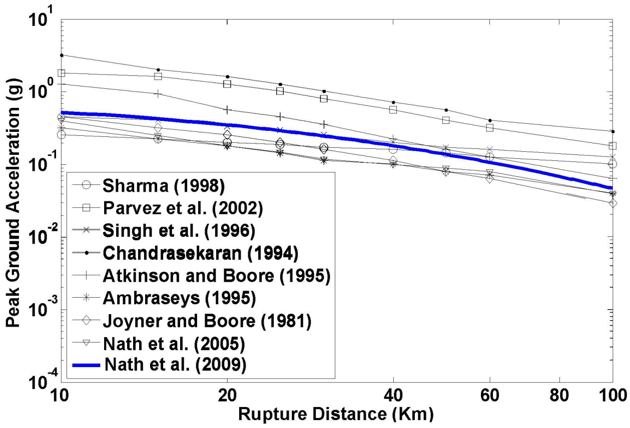

Fig. 5. Some representative ground motion prediction equations: Sharma (1998), Parvez et al. (2002), Singh et al. (1996), and Chandrasekaran (1994) for Himalayas, Atkinson and Boore (1995) for East North America, Ambraseys (1995) for Europe, Joyner and Boore (1981) for California, Nath et al. (2005) for Sikkim Himalaya, and Nath et al. (2009) in northeast India.

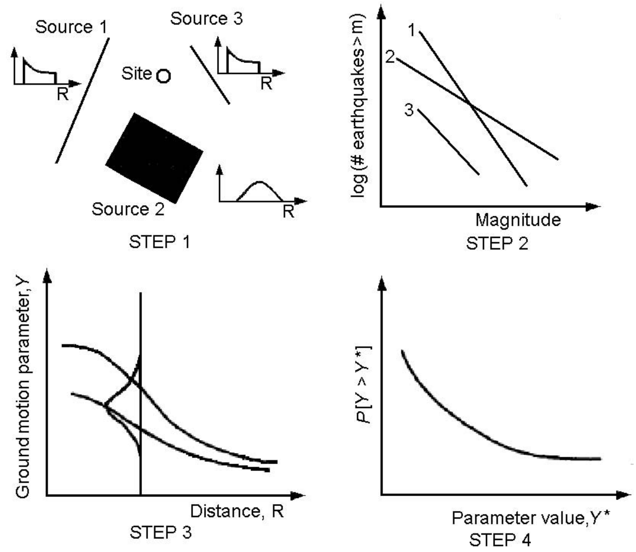

Fig. 6. Four steps of probabilistic seismic hazard analysis (after Reiter, 1990)

and (vi) spectral element method (Komatitsch and Tromp, 1999).

4.6 Development of ground motion prediction equations

The rapid estimations of the ground motion parameters at a site of interest are often achieved by using a ground motion prediction relationship that relates a specific strong ground motion parameter of ground shaking to one or more attributes of an earthquake (e.g. Sadigh et al., 1997; Abrahamson and Silva, 1997; Campbell and Bozorgnia, 2003; Atkinson and Boore, 2003; Nath et al., 2005, 2009). Generally employed ground motion parameters include PGA, PGV, pseudo-spectral acceleration or velocity PSA or PSV, and intensity. These parameters are found to increases with magnitude while decreasing with the epicenter distance and are also controlled by the fault-rupture directivity, and site conditions. Accordingly, the variables used generally include magnitude, distance measures such as hypocentral and fault rupture distance, faulting type and site term. A few examples of strong motion prediction equations are presented in Fig. 5. Incorporation of detailed site classification and a basin-depth effect can be found in Field (2000). Next Generation of ground-motion Attenuation models (NGA) is a recent development aimed at developing new ground-motion prediction relations through a comprehensive and highly interactive research program (Power et al., 2008).

4.7 Probabilistic seismic hazard assessment

Probabilistic Seismic Hazard Assessment (PSHA) incorporates uncertainty and the probability of earthquake occurrences delivering the hazard in probability of non-exceedance (or exceedance) for a specified return period (Cornell, 1968; Reiter, 1990). The conventionally followed steps in the PSHA are depicted in Fig. 6. Probability distributions are determined for the magnitude of each earthquake on each source, and the location of the earthquake in or along each source. The distributions are combined with the source geometry to obtain the probability distribution of source-to-site distance. Recurrence relationships are used to characterize the source seismicity. The ground motion at the site, along with its inherent uncertainty, due to earthquakes of possible magnitudes nucleating from each source is determined through ground motion prediction equations. The uncertainties in earthquake location, size, and the ground motion are combined to obtain the probability that the value of the ground motion parameter will be exceeded in a particular time period. Multiple perspectives and expert opinions are often incorporated in the PSHA using “logic tree” (McGuire, 2004).

4.8 Induced hazard assessments

The secondary phenomena associated with ground shaking include ground spreading, slumping, soil liquefaction, landslide, rockfalls, etc, that contributes to the overall seismic risk.

4.8.1 Liquefaction susceptibility mapping

Soil liquefaction is triggered when loose or soft saturated unconsolidated soil transforms from a solid state to a viscous state due to the increase in pore water pressure and consequent decrease of effective stress. It tends to reoccur at the same sites during successive earthquakes where geological and hydro-geological conditions remain fairly stable. Such sites need to be identified and mapped as a part of rudimentary study supported by a geological map providing detailed Quaternary (recent) deposits at high precisions. Recent sediments especially fluvial and Aeolian deposits, water table information along with physical soil characteristics such as type of soil, degree of water saturation, grain size, and plasticity are key inputs for the liquefaction hazard assessment.

The fine grain criteria for sands (e.g. Wang, 1979; Seed and Idriss, 1982; Bray and Sancio, 2006) allows quick assessment while the standard geotechnical evaluation prospects into the mechanical properties of the soil. A widely used technique is the simplified procedure of Seed and Idriss (1971) and its upgraded versions (Seed and Idriss, 1982). The factor of safety against liquefaction (FSL) is evaluated as "Cyclic Stress Ratio"/"Cyclic Resistance Ratio" i.e. the earthquake induced loading divided by the liquefaction resistance of the soil. Other techniques using CPT or MASW also exist (e.g. Shibata and Teparaska, 1988; Lin et al., 2004). The probabilistic and deterministic assessment of the hazard can be found in Cetin et al. (2004) and Moss et al. (2006). The detailed zonation generally places four classes of hazard namely "no liquefaction" ($FSL >=$2.0), "moderate"($1.5<=FSL <2$), "high" ($1<=FSL <1.5$), and "very high" ($FSL <1.0$).

4.8.2 Landslide hazard zonation

Earthquakes can activate slope failures in the undulating terrains leading to landslides with catastrophic effects. These depend on several factors inherent to the soil conditions such as geology, hydro-geology, topography, and slope stability. The groundwork towards landslide hazard assessment consists of appraising existing information from newspapers, local reportings, and concerned organizations followed by association of the historical landslides into classes of failures and movement. The zonation of landslide hazard defining four degrees of hazards: "nil or low", "moderate", "high", and "very high" can be achieved through several ways–from simplistic analysis based on the preparatory factors i.e. soil and slope conditions, seismicity, water content, rainfall, etc to pseudo-static analysis and finite-element methods for non-linear behavior of the soil response. The deterministic landslide susceptible zones can be developed through preparatory factors without considering the triggering factors (Saha et al., 2005).

The probabilistic evaluation of the seismic landslide hazard dealing with occurrence of an event with specific intensity at a site during a time interval has been considered by Fell (1994), Hungr (1997), and Perkins (1997). The advanced techniques recently proposed by several researchers like Del Gaudio et al. (2003), and Jibson et al. (2000) are inherently rigorous with extensive data inputs comprising of triggered landslides inventory, strong-motion records, geological maps along with engineering properties of different units, and digital elevation models of the topography, and employs dynamic model based on Newmark's permanent-deformation (sliding-block) analysis.

4.8.3 Site classification

Site class specifications are employed to characterize generic subsurface conditions towards seismic response of the soil. The average shear wave velocity of the upper soil column is widely used for the purpose; the ranges of values for each site class corresponding to a specific class of soil. NEHRP (Building Seismic Safety Council, 2001) specifies site class specifications (A–F) on the shear wave velocity averaged for the upper 30 m of the soil column $V_{S,30}$ with the exceptions of site class E and F. The former is identified with the velocity less than 180 m/s or with more than 3 m of soft clay and Plastic index greater than 20, water content more than 40%, and corresponding average undrained shear strength less than 25 kPa. Site F requires site-specific evaluations to identify any of four categories: (1) soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils, (2) peats and/or highly organic clays (soil thickness greater than 3 m) of peat and/or highly organic clay, (3) very high plasticity clays (soil thickness greater than 8 m with plasticity index greater than 75.), and (4) very thick soft/medium stiff clays (soil thickness greater than 36 m). UBC provisions also employ average shear wave velocities to describe the soil coefficients (ICBO, 1994). Geological attributes are often connected to shear wave velocity in view of limited number of observation sites (e.g. Wills and Silva, 1998; Wills and Clahan, 2006). On the basis of the overlapping ranges of $V_{S,30}$ accorded to different geological units, Wills et al. (2000) introduced intermediate classes namely BC, CD, and DE corresponding to an average $V_{S,30}$ of 760 m/s, 360 m/s, and 180 m/s, respectively.

5 Composite hazard evaluation

The composite hazard assessment incorporates multiple attributes through multi-criteria evaluation technique for the spatial delineation. The representative attribution in case of seismological and geological aspects is depicted in Figs. 7 and 8. Fuzzy sets enabled scheme for the representation and manipulation of uncertainty related to the classification of individual locations according to their attribute values can be aided by the Analytic Hierarchy Process (AHP)–a mathematical method introduced by Saaty (1980) to determine priority of criteria in the decision making process (Nath, 2005). AHP uses hierarchical structures to represent a problem and then develop priorities for the alternatives based on the judgment of the experts. Pair-wise comparisons are employed to form judgments between two particular elements rather

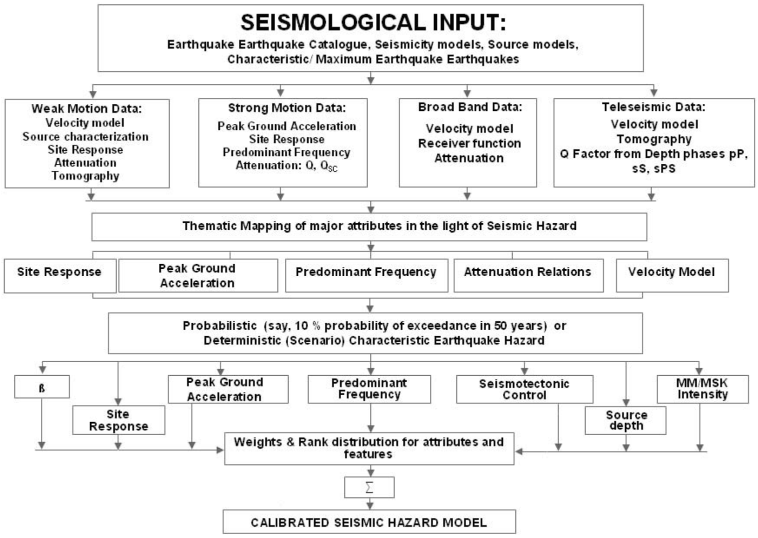

Fig. 7. Seismological aspects in the seismic microzonation model

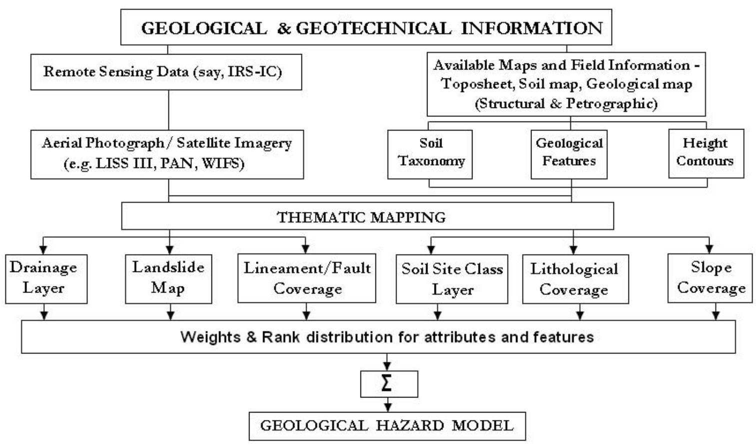

Fig. 8. Geological aspects in the seismic microzonation model

than attempting to prioritize an entire list of elements. The process of allocating weights is a subjective one and can be done in the participatory mode in which a group of decision makers may be encouraged to reach a consensus of opinions about the relative importance of factors. The values within each thematic map/layer varying significantly are classified into various ranges or types, which are referred to as the features of a layer. These features are then assigned ranks or scores within each layer, normalized to ensure that no layer exerts an influence beyond its determined weight. Three case studies are presented in the following subsections.

5.0.4 Regional perspectives on the typical site specific urban case studies

Three microzonation projects in typical geological provinces are taken up for comprehensive discussions. Figure 9 depicts the locations of the study regions, in the Sikkim Himalaya, Guwahati city, and Bangalore mega city. The Sikkim Himalaya represents high seismogenic territory with historical reportings of damaging earthquakes namely 1934 Bihar-Nepal M_w 8.1, 1980 Sikkim M_w 6.3, 1988 Bihar-Nepal M_w 6.8, and 2006 Mana M_w 5.3. In the regional level, the seismic hazard zonation of India puts the region in the high hazard Zone IV (BIS, 2002) while Global Seismic Hazard Assessment programme (GSHAP, Bhatia et al., 1999) predicts high hazards in terms of PGA to the tune of 0.3 g (1 g=980 gal) in the region. The topography in this terrain is an undulating one with significant vulnerability to earthquake triggered landslides. Nevertheless, the region is progressing in the development of its natural resources and improving the quality of life of the inhabitants. Already six hydel power projects have been commissioned in the State with proposal of thirty such projects in this terrain. The Guwahati

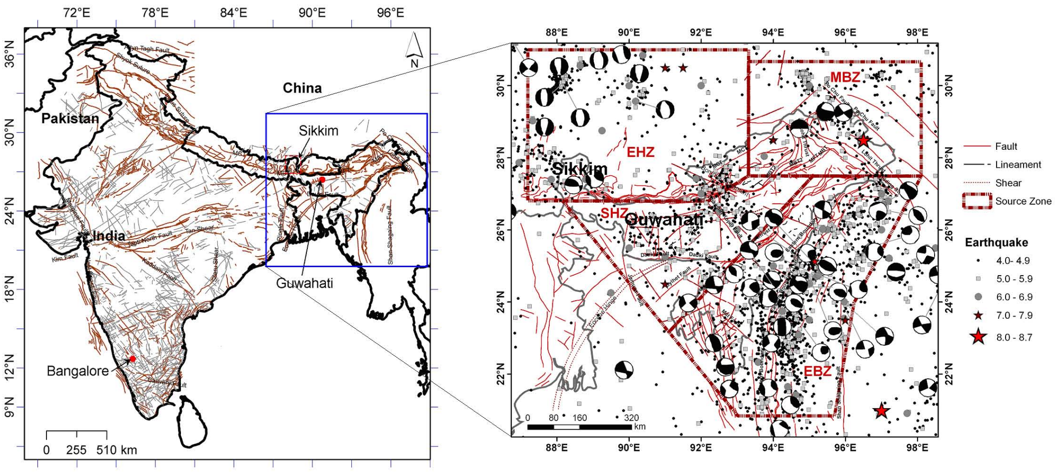

Fig. 9. Left: The location of the case studies presented on a tectonic map of India adapted from Dasgupta et al. (2000). Right: Four seismic source zones classified in the northeast Indian region overlaid on a seismotectonic map (after Thingbaijam et al., 2008).

city, being placed under the Zone V - highest hazard zone classified according to seismic zonation of India (BIS, 2002) and with the GSHAP predicting PGA as high as 0.35 g in the region, besides located on a shallow alluvium basin, providing a suitable case for microzonation study of intense significant. The city also experienced several damaging earthquakes in the past namely 1869 Cachar M_w 7.4, 1897 Shillong M_w 8.1, 1918 Srimangal M_w 7.2, 1930 Dhubri M_w 6.8, and 1950 Assam M_w 8.7. In the recent times, rapid urbanization and population influx has increased the seismic vulnerability and the associated risk in the city. Bangalore city in the southwestern part of India has been the fastest grown mega urban center transformed into satellite Silicon Valley of India, presently ranked as fifth biggest city in India. The metropolis represents a booming commercial center with expansive infrastructure and burgeoning population. The city, overlying a flat topography, is located in a low seismic hazard zone – Zone II of BIS hazard zonation code (BIS, 2002). 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 of the peninsular India that encompasses the city.

Figure 9 also depicts four broad seismic source zones demarcated by Thingbaijam et al. (2008) on the basis of spatial seismicity patterns represented by b-value, and fractal correlation dimension of the epicenters overlaid on the regional tectonic framework. Thingbaijam and Nath (2008) predicted the maximum earthquakes in each zone by means of a maximum likelihood method (Kijko, 2004; Kijko and Graham, 1998) that employs a modified form of the standard Gutenberg-Richter relation with an exponential tail of a Gamma function at larger magnitudes taking into account the uncertainty of the b-value. Maximum earthquakes of M_w 8.3 and 8.7 could be respectively associated with the Eastern Himalayas and the Shillong zone, which corresponds to the major contributing seismic source zones for Sikkim and Guwahati city (Nath et al., 2008b). Sitharam et al. (2006) estimated the maximum earthquake in the Bangalore city through Wells and Coppersmith (1994) relationship between magnitude and fault-rupture length to be M_w 5.1 at the Mandya–Channapatna–Bangalore Lineament to the north of the city and traversing in the E-W direction.

5.0.5 The case of Sikkim Himalaya

The microzonation study in the region has been formulated into two different aspects–geomorphological and seismological. The former is derived from thematic layers comprising of surface geology, soil cover, slope, rock outcrop, and landslide hazard, which are integrated to achieve geological hazard distribution. The corresponding thematic layers have been developed by Nath (2004). The major datasets include IRS–1C LISS III digital data, toposheets from Survey of India, surface geological maps, soil taxonomy map based on composition, grain size and lithology from the National Bureau of Soil Survey and seismic refraction profiles. The percent slope mapping has been done with Triangulated Irregular Network (TIN) on GIS. Rock outcrop and landslide scarp region had been identified and vectorized into two separate polygon coverage. The latter highlights the relevant hazard conduced from seismic activities instead of geotechnical landslide hazard zonation. The seismological themes, namely surface consistent peak ground acceleration and predominant frequency were, thereafter, integrated with the geological hazard distribution to obtain the seismic hazard microzonation map of the Sikkim Himalaya.

Site response in the region is attributed mainly to different source radiation patterns, scattering, diffraction and undulating topographic effects. The study in the region by Nath et al. (2005) comprises of HVSR and GINV techniques

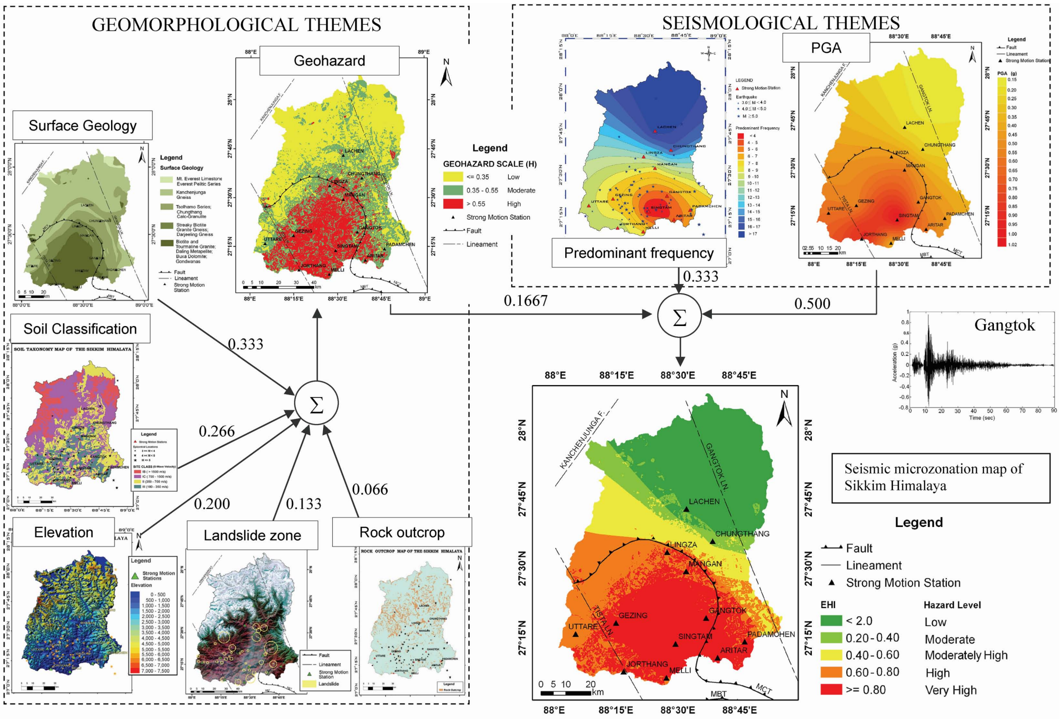

Fig. 10. The seismic microzonation scheme for Sikkim Himalaya with the weights assigned to each theme labeled accordingly leading to the final hazard map. A representative accelerogram simulated at the Gangtok Strong Motion Station for the projected maximum earthquake of M_w 8.3 nucleating from a depth of 26.3 km on MBT is also depicted.

based on 80 local earthquakes ($3 \leq M_L \leq 5.6$) during 1998–2003 recorded by nine stations of IIT Kharagpur Sikkim Strong Motion Array (SSMA). The finite fault stochastic simulation has been used to deliver the surface consistent peak ground acceleration due to the maximum earthquake of M_w 8.3 projected to be nucleating from Main Boundary Thrust (MBT) trending NW-SE in the southern part of the region at a depth of 26.3 km with a fault plane solution providing 310° strike and 35° NNE dip (Nath et al., 2005; Nath et al., 2008b). The adopted simulation parameters are as follows: the designated epicenter at 27.25° N and 88.46° E, rupture dimensions of 250 km length and 80 km width, crustal shear wave velocity of 4.0 km/s, crustal density of 2.7 g/cm^3, stress drop of 65 bars, Quality factor $Q_S = 167 f^{0.47}$ where f is frequency in Hz, and geometrical spreading factor given by $1/R$ for $R < 100$ km and $1/R^{0.5}$ for $R \geq 100$ km where R is the hypocentral distance in km. The final integrated hazard map, as presented in Fig. 10, exhibits five broad qualitative hazard classifications - “Low”, “Moderate”, “High”, “Moderate High” and “Very High”.

5.0.6 The case of Guwahati City

The microzonation study of the city accounts for six themes, namely, geological and geomorphological, basement topography, landslide hazard, site classification, predominant frequency, and the surface consistent peak ground acceleration. The city is covered with recent alluvium with some Archean hillocks exposed at places. The sediment thickness varies from ten to few hundred meters in the region, which is the likely contributor of site specific ground motion amplifications.

The thematic layers have been discussed by Nath et al. (2007) and Nath et al. (2008b). The geological and geomorphological map, generated using Survey of India (SOI) topographic maps, IRS PAN and LISS III satellite images in digital format and extensive GPS based point surveys, classifies the major soil aggradational units along with geological formations, river and water bodies. The basement topography is prepared from the results of vertical electrical resistivity soundings carried out by Geological Survey of India (GSI), and the data obtained from 30 boreholes. Landslide hazard zones have been demarcated in the region in deterministic terms using slope angle, lithological structures, relative relief, landuse cover, hydrological correlation, seismicity, rainfall, and landslide incidences. The site classification, mostly under site class-D, is achieved through the $V_{S,30}$ distribution obtained from SPT data at 200 borehole sites across the region (Nath et al., 2008b) along with the susceptible zones identified by the estimated factor of safety against soil liquefaction at the borehole sites indicated as site class F, and surficial geology identifying site class CD and rock sites.

The zones of site class E are also identified from the bore logs. Nath et al. (2008a) estimated the site response distribution in the region from the geotechnical data at 200 boreholes across the region as well as strong motion data of five events ($4.8 \leq m_b \leq 5.4$) that occurred during 2006. The amplification of ground motion over soft sediments occurs fundamentally due to the trapping of seismic waves and the resulting impedance contrast between sediments and the underlying bedrock. These trapped waves interfere with each other to produce resonance patterns, the shape and the frequencies that are correlated with the geometrical and mechanical characteristics of the structure. The strong ground motion data analyses were achieved through the HVSR technique at different source azimuths for various sites. The geotechnical analyses were performed through SHAKE 2000 (Ordonez, 2004) at all the 200 borehole locations. The site response estimated from strong motion stations and closely located boreholes are calibrated, which exhibited the latter to be average values. The predominant frequency distribution in the region has been assessed through ambient noise data analysis at 141 locations by Nath et al. (2008a). Nath et al. (2009) generated the deterministic seismic scenario represented by surface consistence PGA in the city from the controlling source placed at the 1897 Shillong earthquake with the maximum earthquake of M_w 8.7. The simulation parameters are strike 112° SE, dip 40° ESE, focal depth of 35 km, epicenter at 26° N and 91° E, fault rupture dimension of 330 km length and 150 km width, crustal shear wave velocity of 3.25 km/s, crustal density of 2.7 g/cm^3, stress drop of 159 bars, Quality factor $Q_S = 342 f^{0.72}$ where f is frequency in Hz, and geometrical spreading defined by $1/R$ for $R < 100$ km, and $1/R^{0.5}$ for $R > 100$ km where R is the hypocentral distance in km. The thematic integration scheme implemented for Guwahati city is depicted in Fig. 11. Five broad qualitative hazard classifications – "Low", "Moderate", "High", "Moderate High" and "Very High" could be applied.

5.0.7 The case of Bangalore Mega City

The seismic microzonation study in the city involved evaluation of different seismic hazard components 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.

Sitharam et al. (2007) derived a sub-surface model from geotechnical bore-log data and subsequently the overburden thickness distribution in the city, predominantly in the range of 5–10 m. Anbazhagan and Sitharam (2008a) estimated the effective shear wave velocity distribution in the city through MASW survey and with subsequent data interpretation through dispersion analysis identified zones of NEHRP site class D, C and B in the city. The peak ground acceleration at the bedrock level has been estimated through deterministic approach by Sitharam and Anbazhagan (2007) based on the maximum earthquake of M_w 5.1 assumed to be nucleating from the closest active seismic source namely Mandya–Channapatna–Bangalore Lineament. The simulation was performed with the point-source stochastic simulation algorithm of Boore (1983) at 620 borehole locations where the basement depth information is available. The maximum earthquake has been placed at the focal depth of 15 km, the average crustal shear wave velocity taken to be 3.65 km/s, the geometric attenuation G taken to be $1/R$ for $R < 100$ km and $1\sqrt{R}$ for $R > 100$ km where R is the hypocenter distance in km, the quality factor $Q(f)$ taken to be equal to $488 f^{0.88}$ where f is the frequency in Hz, stress drop of 300 bars, and the high-frequency band-limitation parameter, $f_{\max}$, set to 35 Hz has been considered. Sitharam and Anbazhagan (2008b) employed 170 geotechnical bore logs and 58 shear wave velocity profiles to compute the site effects through one-dimensional ground response analysis with SHAKE2000 delivering the site amplification factor and predominant frequency distributions in the city. Sitharam et al. (2007) estimated the soil liquefaction hazard in the city in terms of factor of safety against liquefaction potential using standard penetration test data and the underlying soil properties. The spatial distributions of the different hazard entities are placed on a GIS platform and subsequently, integrated through analytical hierarchal process as illustrated in Fig. 12.

6 Risk assessment

The exposures of the vulnerability components such as human population, buildings, etc to the seismic hazard characterize seismic risk of a region. The seismic hazard is generally assumed to be stable over a long geological time while the typical vulnerability (and therefore, the risk) to the hazard changes (McGuire, 2004). The risk is assessed as a convolution function of the hazard and the vulnerability i.e. **Risk=Hazard * Vulnerability**. The risk appraisals, aimed at promoting reasonable hazard mitigation regulations, are generally based on vulnerability aspects such as landuse, demographic distributions, building typology, etc.

The computation of risk is fundamentally influenced by that of the hazard. Likewise, seismic risk assessment could be deterministic or probabilistic. The former involves direct assessment of possible losses based on the results of deterministic hazard analysis with no involvement of reference time period but yielding to the current status. The assessment could, otherwise, follow either mean values or take into account the uncertainties related to frequency of event occurrences (hazard) and damage levels (vulnerability) yielding to a probabilistic account of the expected losses (Giacomo et al., 2005). These approaches allow estimation of risk on a reference period of time. Another approach is to generate the probable damage scenario by random simulations based on post earthquake damage studies (Barbat et al., 1996). An example of deterministic assessment leading to

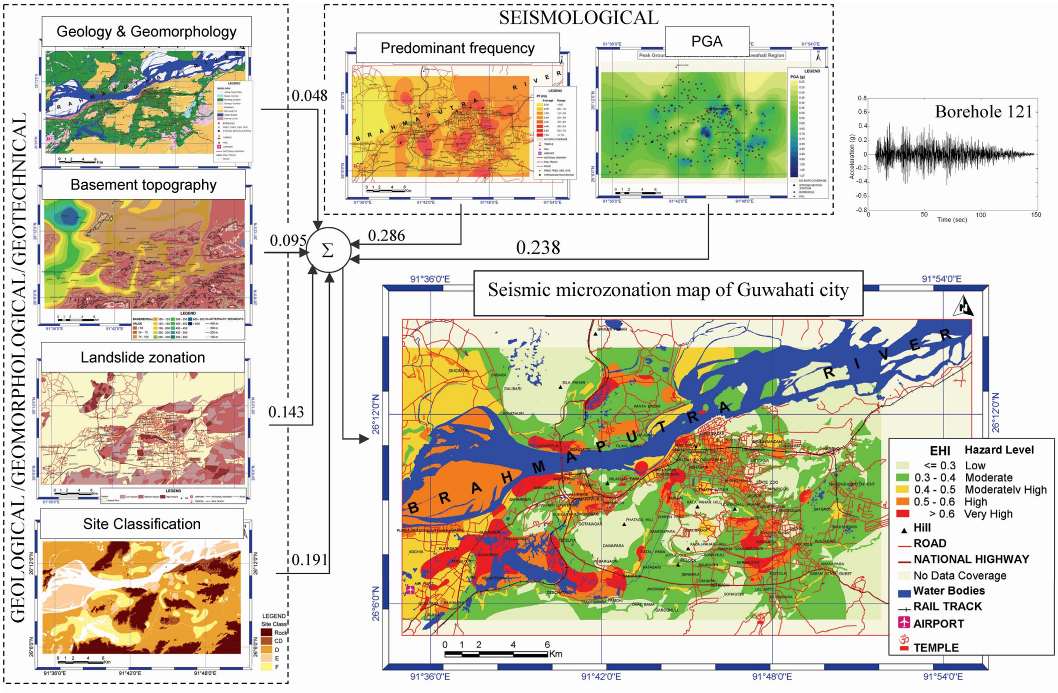

Fig. 11. The seismic microzonation scheme for Guwahati city with the weights assigned to each theme labeled accordingly leading to the final hazard map. A representative accelerogram simulated at a borehole location for the projected maximum earthquake of M_w 8.3 nucleating from the Shillong seismic zone is also depicted.

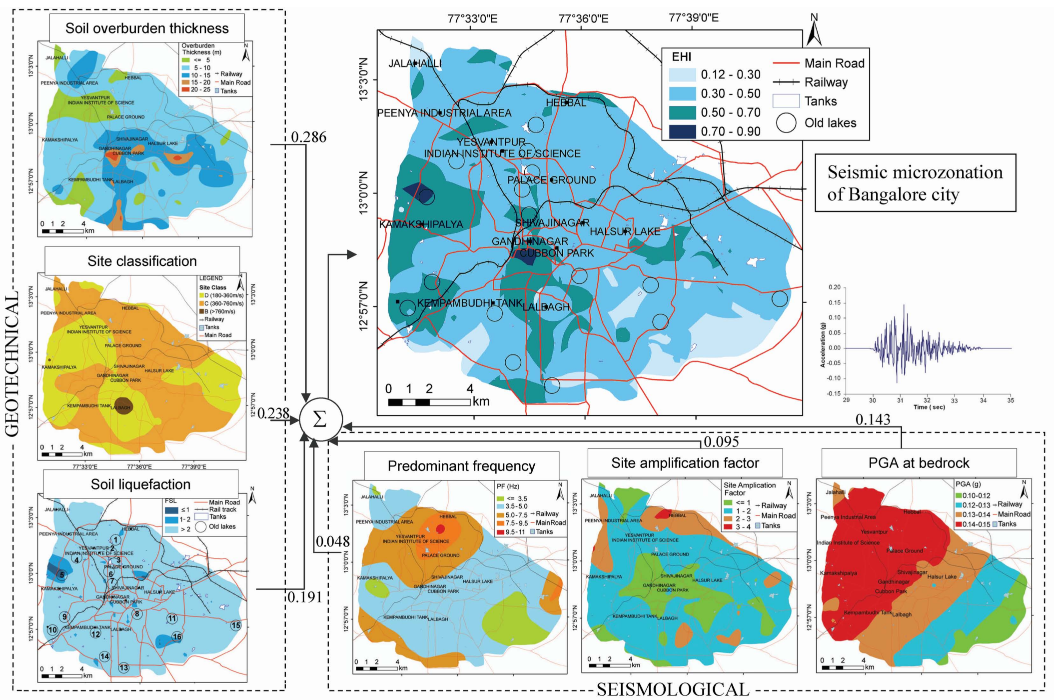

Fig. 12. The seismic microzonation scheme for Bangalore city with the weights assigned to each theme labeled accordingly leading to the final hazard map. A representative accelerogram simulated at bedrock level for a projected maximum earthquake of M_W8.3 nucleating from Mandya–Channapatna–Bangalore Lineament is also depicted.

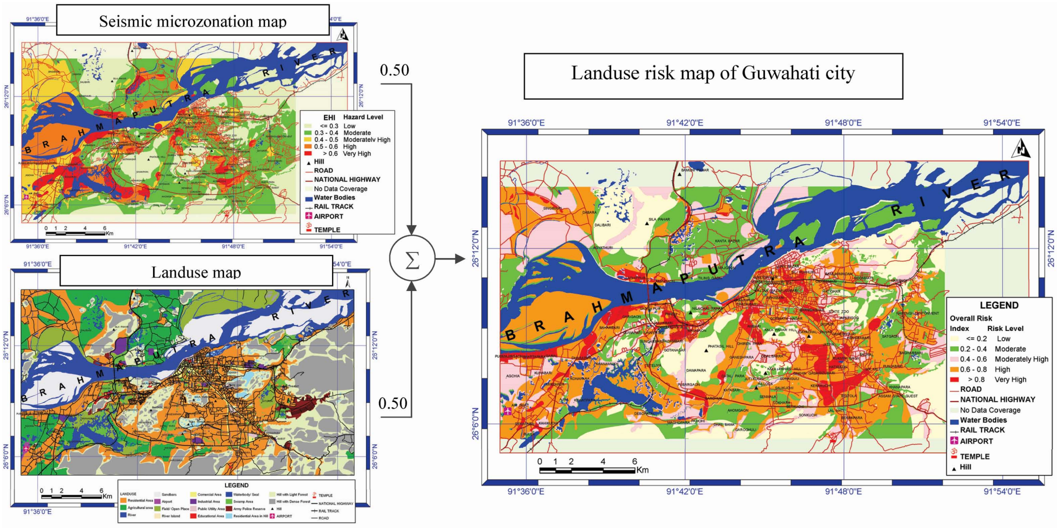

Fig. 13. A preliminary current risk map drawn from the thematic integration of seismic microzonation (hazard) and landuse (vulnerability) maps.

first cut examination of the current risk distribution for the Guwahati city based on landuse patterns using multi-criteria evaluation technique is depicted in Fig. 13.

7 Concluding remarks

The geological and geotechnical site conditions greatly influence the strong ground motion at a site. The basement topography represented by the soil overburden thickness is connected to the site specific hazard, especially if contrast exists in geophysical properties between the basement and the soil deposits. The sediment thickness implicates rebounding of the seismic waves leading to site amplifications, and therefore, has direct implications. Likewise undulating topography (elevations) would produce scattering, focusing, or defocusing of incident seismic waves. The shear wave velocity averaged over 30 m of the soil column is used for site classifications towards generic seismic response of the soil, thus allowing rapid assessment of site conditions, especially in urban settings. Another hazard factor is the soil liquefaction, which is connected to loose soil and geo-hydrological conditions, and therefore, is a determinant geotechnical hazard, especially at the reclaimed sites previously of natural water bodies, and swampy tracts. In hilly terrains, on the other hand, seismic landslide is foremost determinant induced hazard. The underlying primary hazard is generally represented by peak ground acceleration, a short period ground motion parameter signifying damage potential to the buildings enabling an overall quantitative basis for the design codes and construction practices. However, when the analysis is targeted at specific buildings, period-specific spectral acceleration would also be a better index to account for applicable resonance frequencies. The typical case examples in this paper employ predominant frequency in the multi-criteria assessment to derive generic hazard conditions. Period specific analyses based on spectral accelerations are envisaged for building typological specific and ward-wise studies. The amalgamation of the different hazard factors are aimed at the better representation of the local specific seismic hazard variation in the study regions.

The seismic microzonation has emerged as an important issue in high risk urban centers across the globe. The compilation of data pertaining to geological, geophysical, geotechnical and seismological aspects comprises a major part of the venture, which necessitates a consortium of several public and private organizations engaged in diversified but related domains. The effort towards enhancing our understanding of the seismic hazard and related effects is an on-going process, and therefore, the framework and tools for the seismic microzonation studies presented here needs to be continuously updated in the light of ongoing advancements as well as experiences gained during earthquakes. It is expected that seismic microzonation will enable updating building codes as well as formulate actions for hazard mitigation at sub-regional and local levels. Active programs related to infrastructural improvements and response planning can led to reduction of seismic risk.

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References

Abrahamson, N. A. and Silva, W. J.: Empirical response spectral attenuation relations for shallow crustal earthquakes, Seis. Res. Lett., 68, 94–127, 1997.

Aki, K.: Local site effect on strong ground motion, Proc. Earthq. Eng. Soil. Dyn. II, Park City, Utah, 27-30 June, ASCE, 103-155, 1988.

Ambraseys, N. N.: The prediction of earthquake peak ground acceleration in Europe, Earthq. Eng. Struct. Dyn., 24, 467–490, 1995.

Anbazhagan, P. and Sitharam, T. G.: Mapping of average shear wave velocity for Bangalore region: a case study, J. Env. Eng. Geophys., 13, 69–84, 2008a.

Anbazhagan, P. and Sitharam, T. G.: Seismic microzonation of Bangalore, India, J. Earth Sys. Sci., 117, 833–852, 2008b.

Anderson, J. G., Wesnousky, S. G., and Stirling, M. W.: Earthquake size as a function of fault slip rate, Bull. Seis. Soc. Am., 86, 683–690, 1996.

Atkinson, G. M. and Boore, D. M.: Empirical ground-motion relations for subduction-zone earthquakes and their applications to Cascadia and other regions, Bull. Seis. Soc. Am., 93, 1703–1729, 2003.

Barbat A. H., Moya, F. Y., and Canas, J. A.: Damage scenarios simulation for seismic risk assessment in urban zones, Earthq. Spect., 12(3), 371–394, 1996.

Bard, P. Y., Czitrom, C., Durville, J. L., Godefroy, P., Meneroud, J. P., Mouroux, P., and Pecker, A.: Guidelines for seismic microzonation studies, published by Delegation of major risks of the French Ministry of the environment-direction for prevention, pollution and risks, 1995.

Beresnev, I. A. and Atkinson, G. M.: Modelling finite-fault radiation from the ω^n spectrum, Bull. Seis. Soc. Am., 87, 67–84, 1997.

Bhatia, S. C., Kumar, M. R., and Gupta, H. K.: A probabilistic seismic hazard map of India and adjoining regions, Ann. Geofis., 42, 153–1164, 1999.

BIS: 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, 2002.

Boore, D. M.: Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, Bull. Seis. Soc. Am., 73, 1865–1894, 1983.

Boore, D. M. and Atkinson, G. M.: Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America, Bull. Seis. Soc. Am., 77, 440–467, 1987.

Bouchon, M. and Aki, K.: Discrete wave-number representation of seismic-source wave fields, Bull. Seis. Soc. Am., 67, 259–277, 1977.

Bray, J. D. and Sancio, R. B.: Assessment of the liquefaction susceptibility of fine-grained soils, J. Geotech. Geoenv. Eng., 132, 1165–1177, 2006.

Building Seismic Safety Council: NEHRP recommended provisions for seismic regulations for new buildings and other structures, 2000 Edition, Part 1: Provisions, Building Seismic Safety Council for the Federal Emergency Management Agency (Report FEMA 368), Washington, D.C., 2001.

Campbell, K. W. and Bozorgnia, Y.: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra, Bull. Seis. Soc. Am., 93, 314–331, 2003.

Cetin, K. O., Seed, R. B., Der Kiureghian, A., Tokimatsu, K., Harder, L. F., Kayen, R. E., Moss, R. E. S.: Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential, J. Geotech. Geoenv. Eng., ASCE, 130, 1314–1340, 2004.

Chandrasekaran, A. R.: Evaluation of design earthquake parameters for a site and utilization of strong motion data, Curr. Sci., 67, 353–358, 1994.

Cornell, C. A.: Engineering seismic risk analysis, Bull. Seis. Soc. Am., 58, 1583–1606, 1968.

Dasgupta, S., Pande, P., Ganguly, D., et al.: Seismotectonic Atlas of India and its Environs, Geological Survey of India, Calcutta, India, 2000.

Del Gaudio, V., Pierri, P., and Wasowski, J.: An approach to time-probability evaluation of seismically induced landslide hazard, Bull. Seis. Soc. Am., 93, 557–569, 2003.

Fell, R.: Landslide risk assessment and acceptable risk, Can. Geotech. J., 31, 261–272, 1994.

Field, E. H.: A modified ground-motion attenuation relationship for southern California that accounts for detailed site classification and a basin depth effect, Bull. Seis. Soc. Am., 90, S209–S221, 2000.

Frankel, A.: A review of numerical experiments on seismic wave scattering, Pageoph, 131, 639–685, 1989.

Fumal, T. E. and Tinsley, J. C.: Mapping shear-wave velocities of near-surface geologic materials. Evaluating Earthquake Hazards in the Los Angeles Region - An Earth-Science Perspective, Ziony J. I. (Ed.), U.S. Geological Survey Prof. Paper, 1360, 127–149, 1985.

Giacomo, P., Giampiero, O., Roberto, R.: New Developments in Seismic Risk Assessment in Italy, Bulletin of Earthquake Engineering, 3, 101–128, 2005.

Hanks, T. C. and Bakun, W. H.: A bilinear source-scaling model for M-log A observations of continental earthquakes, Bull. Seis. Soc. Am., 92, 1841–1846, 2002.

Hartzell, S. H.: Earthquake aftershocks as Green's functions, Geophys. Res. Lett., 5, 1–5, 1978.

Hartzell, S. H.: Site response estimation from earthquake data, Bull. Seis. Soc. Am., 82, 2308–2327, 1992.

Hough, S. E. and Bilham, R.: Site response of the Ganges basin inferred from re-evaluated macro-seismic observations from the 1897 Shillong, 1905 Kangra, and 1934 Nepal earthquakes, J. Earth Sys. Sci., 117, 773–782, 2008.

Hungr, O.: Some methods of landslide intensity mapping, in Landslide Risk Assessment, D. M. Cruden and R. Fell (Editors), Balkema, Rotterdam, 215–226, 1997.

Ibs-von Seht, M. and Wohlenberg, J.: Microtremor measurements used to map thickness of soft sediments, Bull. Seis. Soc. Am., 89, 250–259, 1999.

ICBO: Uniform Building Code, 1991, International Conference of Building Officials, Whittier, California, 1994.

Imai, T. and Tonouchi, K.: Correlation of N-value with S-wave velocity and shear modulus, Proc. 2nd Euro. Sym. Penet. Test., Amsterdam, 57–72, 1982.

Irikura, K.: Semi-empirical estimation of strong ground motions during large earthquakes, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 33, 63–104, 1983.

Jibson, R. W., Harp, E. L., and Michael, J. A.: A method for producing digital probabilistic seismic landslide hazard maps, Eng.

Geo., 58, 271–289, 2000.

Joyner, W. B. and Boore, D. M.: Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley, California, earthquake, Bull. Seis. Soc. Am., 71, 2011–2038, 1981.

Kato, K., Aki, K., and Takemura, M.: Site amplification from coda waves: Validation and application to S-wave site response, Bull. Seis. Soc. Am., 85, 467–477, 1995.

Kijko, A.: Estimation of the maximum earthquake magnitude m_{max}, Pageoph, 161, 1–27, 2004.

Kijko, A. and Graham, G.: "Parametric-historic" Procedure for probabilistic seismic hazard analysis. Part I: Assessment of maximum regional magnitude m_{max}, Pageoph, 152, 413–442, 1998.

Komatitsch, D. and Tromp, J.: Introduction to the spectral-element method for 3-D seismic wave propagation, Geophys. J. Int., 139, 806–822, 1999.

Kramer, S. L.: Geotechnical Earthquake Engineering, Prentice Hall Inc., 1996.

Lermo, J. and Chávez-García, F. J.: Site effect evaluation using spectral ratios with only one station, Bull. Seis. Soc. Am., 83, 1574–1594, 1993.

Lin, C. P., Chang, C. C., and Chang, T. S.: The use of MASW method in the assessment of soil liquefaction potential, Soil. Dyn. Earthq. Eng., 24, 689–698, 2004.

McGuire, R. K.: Seismic hazard and risk analysis, Earthquake Engineering Research Institute (EERI), Oakland, 2004.

Moss, R. E. S., Seed, R. B., Kayen, R. E., Stewart, J. P., and Der Kiureghian A.: CPT-based Probabilistic and deterministic assessment of in situ seismic soil liquefaction potential, J. Geotech. Geoenv. Eng. 132, 1032–1051, 2006.

Motazedian, D. and Atkinson, G. M.: Stochastic finite-fault modeling based on a dynamic corner frequency, Bull. Seis. Soc. Am., 95, 995–1010, 2005.

Nakamura, Y.: A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, Quart. Rep. Rail. Tech. Res. Inst., 30, 25–33, 1989.

Nath, S. K.: Seismic hazard mapping and microzonation in the Sikkim Himalaya through GIS integration of site effects and strong ground motion attributes, Nat. Haz., 31, 319–342, 2004.

Nath, S. K.: An initial model of seismic microzonation of Sikkim Himalaya through thematic mapping and GIS integration of geological and strong motion features, J. Asian Earth Sci., 25, 329–343, 2005.

Nath, S. K., Biswas, N. N., Dravinski, M., and Papageorgiou, A. S.: Determination of S-wave site response in Anchorage, Alaska in the 1-9 Hz frequency band, Pageoph, 159, 2673–2698, 2002a.

Nath, S. K., Raj, A., Sharma, J., Thingbaijam, K. K. S., et al.: Site amplification, Qs and source parameterization in Guwahati region from seismic and geotechnical analysis., Seis. Res. Lett., 79, 498–511, 2008a.

Nath, S. K., Raj A., Thingbaijam, K. K. S., and Kumar, A.: Ground motion synthesis and seismic scenario in Guwahati City–A stochastic approach, Seis. Res. Lett., 80, 233–242, 2009.

Nath, S. K., Sengupta, P., and Kayal, J. R.: Determination of Site Response at Garhwal Himalaya from the aftershock sequence of 1999 Chamoli Earthquake, Bull. Seis. Soc. Am., 92, 1072–1081, 2002b.

Nath, S. K., Thingbaijam, K. K. S., and Raj, A.: Earthquake hazard in the northeast India–a seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city, J. Earth. Sys. Sci., 117, 809–831, 2008b.

Nath, S. K., Thingbaijam, K. K. S., Raj, A., et al.: Seismic Scenario of Guwahati City, Proc. Int. workshop on Earthq. Haz. Mitigations, 210–218, 2007.

Nath, S. K., Vyas, M., Pal I., and Sengupta, P.: A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry, J. Geophys. Res., 110, B01301, doi:10.1029/2004jb003199, 2005.

Navarro, N. and Oliveiram C. S.: Experimental techniques for assessment of dynamic behavior of buildings, Assessing and managing earthquake risk: geo-scientific and engineering knowledge for earthquake risk mitigation: developments, tools, techniques, Geotechnical and Earthquake Engineering, Oliveira, C. S., Roca, A., Goula, X. (Eds.), Springer, 2006.

Oprsal, I. and Zahradnik, J.: Three-dimensional finite difference method and hybrid modeling of earthquake ground motion, J. Geophys. Res., 107, doi:10.1029/2000JB000082, 2002.

Ordonez, G. A.: SHAKE2000 a computer program for the 1 D analysis of geotechnical earthquake engineering problems user's manual, 2004.

Panizza, M.: Geomorphology and seismic risk, Earth Sci. Rev., 31, 11–20, 1991.

Panza, G. F.: Synthetic seismograms: the Rayleigh waves modal summation, J. Geophys 58, 125–145, 1985.

Park, C. B., Miller R. D., and Xia J.: Multi-channel analysis of surface waves, Geophysics, 64, 800–808, 1999.

Parolai, S., Bormann, P., and Milkereit, C.: New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V Ratio of seismic noise for the Cologne Area (Germany), Bull. Seis. Soc. Am., 92, 2521–2527, 2002.

Parvez, I. A., Panza, G. F., Gusev, A. A., and Vaccari, F.: Strong-motion amplitudes in Himalayas and a pilot study for the deterministic first-order microzonation in a part of Delhi city, Curr. Sci., 82, 158–166, 2002.

Perkins, D. M.: Landslide hazard maps analogues to probabilistic earthquake ground motion hazard maps, in Landslide Risk Assessment, Cruden, D. M. and Fell, R. (Editors), Balkema, Rotterdam, 327–332, 1997.

Power, M., Chiou, B., Abrahamson, N. A., Roblee, C., Bozorgnia, Y., and Shantz, T.: An Introduction to NGA, Earthq. Spect., 24, 3–21, 2008.

Rajendran, C. P., Rajendran, K., Duarah, B. P., Baruah, S., and Earnest, A.: Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism, Tectonics, 23, TC4009, doi:10.1029/2003TC001605, 1–12, 2004.

Reiter, L.: Earthquake hazard analysis, Issues and Insights, Columbia University Press, New York, 1990.

Saaty, T. L.: The analytic hierarchy process, McGraw-Hill, New York, NY, 1980.

Sadigh, K., Chang, C. Y., Egan, J. A., Makdisi, F., and Youngs, R. R.: Attenuation relationships for shallow crustal earthquakes based on California strong motion data, Seis. Res. Lett., 68, 180–189, 1997.

Saha, A. K., Gupta, R. P., Sarkar, I., Arora, M. K., and Csaplovics, E.: An approach for GIS-based statistical landslide susceptibility zonation - with a case study in the Himalayas, Landslides, 2, 61–

69, 2005.

Seed, H. and Idriss I. M.: Ground motions and soil liquefaction during earthquakes, published by Earthquake Engineering Research Institute, Berkeley, California, USA, 1982.

Seed, H. B. and Idriss, I. M.: Simplified procedure for evaluating soil liquefaction potential, J. Soil Mech. Foun. Div. ASCE, 97, 1249–1273, 1971.

Sharma, M. L.: Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India, Bull. Seis. Soc. Am., 88, 1063–1069, 1998.

Shibata T. and Teparaska, W.: Evaluation of liquefaction potentials of soils using cone penetration tests, Soils Found., 28, 49–60, 1988.

Singh, R. P., Aman, A., and Prasad, Y. J. J.: Attenuation relations for strong seismic ground motion in the Himalayan region, Pageoph, 147, 161–180, 1996.

Sitharam, T. G. and Anbazhagan, P.: Seismic hazard analysis for Bangalore region, Nat. Haz., 40, 261–278, 2007.

Sitharam, T. G., Anbazhagan, P., and Ganesha Raj, K.: Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore, Nat. Haz. Earth Sys. Sci., 6, 927–939, 2006.

Sitharam, T. G., Anbazhagan. P., Mahesh. G. U.: Liquefaction hazard mapping using SPT data, Ind. Geotech. Jour., 37, 210–226, 2007.

Stokoe II K. H., Wright S. G., Bay J. A., and Roesset J. M.: Characterization of geotechnical sites by SASW method, Geophysical Characterization of Sites, Woods R. D. (Ed.), Oxford & IBH Pub. Co., New Delhi, India, 15–25, 1994.

Thingbaijam, K. K. S., and Nath S. K.: Estimation of maximum earthquakes in northeast India region, Pageoph, 165, 1–13, 2008.

Thingbaijam, K. K. S., Nath, S. K., Yadav, A., Raj, A., Walling, Y. M., Mohanty, W. K.: Recent seismicity in northeast India and its adjoining region, J. Seis., 12, 107–123, 2008.

Wang, W.: Some findings in soil liquefaction, Water Conservation and Hydroelectric Power Scientific Research Institute Report, Beijing, China, 1–17, 1979.

Wells, D. L. and Coppersmith, K. L.: New empirical relationships among magnitude, rupture width, rupture area, and surface displacement, Bull. Seis. Soc. Am., 84, 974–1002, 1994.

Wills, C. J. and Clahan, K. B.: Developing a map of geologically defined site condition categories for California, Bull. Seis. Soc. Am., 96, 1483–1501, 2006.

Wills, C. J. and Silva, W. J.: Shear-wave velocity characteristics of geologic units in California, Earthq. Spect., 14 (3), 533–556, 1998.

Wills, C. J., Petersen, M. D., Bryant, W. A., Reichle, M. S., et al.: A site-conditions map for California based on geology and shear wave velocity, Bull. Seis. Soc. Am., 90, S187–S208, 2000.

Woo, G.: Kernel estimation methods for seismic hazard area source modeling, Bull. Seis. Soc. Am., 86, 353–362, 1996.