Review Paper:

Method for Seismic Microzonation with Geotechnical Aspects

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Abstract

This study presents an overview of seismic microzonation and existing methodologies with a newly proposed methodology covering all aspects. Earlier seismic microzonation methods focused on parameters that affect the structure or foundation related problems. But seismic microzonation has generally been recognized as an important component of urban planning and disaster management. So seismic microzonation should evaluate all possible hazards due to earthquake and represent the same by spatial distribution. This paper presents a new methodology for seismic microzonation which has been generated based on location of study area and possible associated hazards.

This new method consists of seven important steps with defined output for each step and these steps are linked with each other. Addressing one step and respective result may not be seismic microzonation, which is practiced widely. This paper also presents importance of geotechnical aspects in seismic microzonation and how geotechnical aspects affect the final map. For the case study, seismic hazard values at rock level are estimated considering the seismotectonic parameters of the region using deterministic and probabilistic seismic hazard analysis. Surface level hazard values are estimated considering site specific study and local site effects based on site classification/ characterization.

The liquefaction hazard is estimated using standard penetration test data. These hazard parameters are integrated in Geographical Information System (GIS) using Analytic Hierarchy Process (AHP) and used to estimate hazard index. Hazard index is arrived by following a multi-criteria evaluation technique - AHP, in which each theme and features have been assigned weights and then ranked respectively according to a consensus opinion about their relative significance to the seismic hazard.

The hazard values are integrated through spatial union to obtain the deterministic microzonation map and probabilistic microzonation map for a specific return period. Seismological parameters are widely used for microzonation rather than geotechnical parameters. But studies show that the hazard index values are based on site specific geotechnical parameters.

Keywords: Microzonation, hazard, site characterization, site response study, liquefaction.

Introduction

In the last three decades, large earthquakes have caused massive loss of lives and extensive physical destruction throughout the world (Armenia, 1988; Iran, 1990; US, 1994; Japan, 1995; Turkey, 1999; Taiwan, 1999, India 2001, Sumatra 2004, Pakistan 2005, China 2008, Haiti 2010 and Japan 2011). India has been facing threat from earthquakes since ancient times. In India, the recent destructive earthquakes are Killari (1993), Jabalpur (1997), Bhuj (2001), Sumatra (2004) and Indo-Pakistan (2005). Many earthquakes in the past have left many lessons that still have to be learnt which are very essential to plan infrastructure and even to mitigate such calamities in future. Very preliminary process of reducing the effects of earthquake is by assessing the hazard itself. Seismic hazard of the region has been represented in the form of zonation map. Seismic zonation is usually carried out in two parts, one at macro level and another at micro level. For a larger area like zonation of country or continent macro level is adopted.

Macrozonation is carried out considering the seismicity, geology in lager scales without considering geotechnical aspects. But microzonation is carried out in smaller scale by considering regional seismicity, geology and local site conditions. Micro level zonations are becoming important for the cities and urban centers due to increasing population agglomeration in the cities, which result in rapid and unplanned constructions. The cities are more hazardous and high risk areas even for the moderate earthquakes. Seismic Microzonation is the first step to minimize seismic related loss of lives and damages. Microzonation has generally been recognized as the most accepted tool in seismic hazard assessment and risk evaluation and it is defined as the zonation with respect to ground motion characteristics taking into account the source and site conditions[81].

Making improvements on the conventional macrozonation maps and regional hazard maps, microzonation of a region generate detailed maps that predict the hazard at much smaller scales. Seismic microzonation is the generic name for subdividing a region into individual areas having different potentials, hazardous earthquake effects, defining their specific seismic behavior for engineering design, land-use and urban planning.

The basic steps of seismic microzonation are to model the rupture mechanism at the source of an earthquake, evaluate the propagation of waves through the earth to the top of the bedrock, determine the effects of local soil profile and thus develop a surface hazard map indicating the vulnerability of the area to potential seismic hazards. Essentially microzonation is required to compile three essential components of seismology, geotechnical and structural engineering. Each component has to be dealt separately in detail and represent variation of the essential parameters and then compile in fashion to give final map for land use, city planning, disaster management and planning and post earthquake relief work. Seismic Microzonation falls into the category of "applied research". That is why it has to be upgraded and revised based on the latest information.

Seismology component involves understating seismicity of region and compiling available geology data, deep geophysical data and earthquake data. Seismotectonic map has to be prepared to show seismic sources and with past earthquakes to depict seismology component. This is the base for seismic hazard analysis, where rock level hazard parameters in the form of spectral or peak ground acceleration are mapped. Second component consists of understanding geotechnical character of study area, estimating the modification of seismic waves and its induced effects. Basically this involves assessment of different effects due to seismic hazard identified in the seismology component.

These two components will be dealt in detail and discussed with respect to the seismic zonation mapping. Third component involves assessment of damage potential of buildings in the region and cost assessment which are called as seismic vulnerability and risk assessment.

Seismic Microzonation

Many countries have initiated seismic microzonation studies with emphasis on site effects around the world, because of the increasing earthquake damages due to ground motion/site effects. Researchers are trying to develop regional level hazard maps considering different earthquake effects. Damages of buildings during an earthquake occur due to change in soil behavior for an earthquake loading. These are called as site effects and induced effects which are primarily based on geotechnical properties of the subsurface materials. Site effects are the combination of soil and topographical effects which can modify (amplify and deamplify) the characteristics (amplitude, frequency content and duration) of the incoming wave field. Induced effects are liquefaction, land slide and Tsunami hazards. Amplification and liquefaction are major effects of earthquake that cause massive damages to infrastructures and loss of lives.

Recent study by USGS revealed that among deadly earthquakes reported in the last 40 years, loss of lives and damages caused by ground shaking hazard was more than 80% of the total damages[55]. Subsurface soil layers play a very important role in modifying ground shaking. Most of the earthquake geotechnical engineers are working on how to estimate accurately ground shaking hazards by incorporating geotechnical aspects to minimize damages and loss of lives. The geotechnical engineers are responsible for providing the appropriate site-specific design ground motions for earthquake resistant design of structures to the structural engineers. Many of seismic microzonation studies have given emphasis to this geotechnical aspect, but one should remember that improper assessment of seismic hazard will lead to wrong geotechnical hazard parameters in seismic microzonation.

Any seismic microzonation study neglecting the probable earthquake characteristics and the effect of the incoming seismic wave would be incomplete.[1,29] In most general terms, seismic microzonation is the process of estimating the response of soil layers under earthquake excitations and thus the variation of earthquake induced effects on the ground surface. However, it is also very important to select appropriate ground motion parameters for microzonation that correlate with the observed structural damage.[42]

The first attempt of seismic microzonation of urban area i.e. an industrial as well as population center was carried out in city of Yokohama, Japan in 1954 considering various zones, corresponding soil conditions and design seismic coefficients for different types of structures located in different zones. Subsequently, in the view of immense usefulness, microzonation studies were conducted in few earthquake prone areas of the World.[2,22,34,39,40,54,56] Slob et al[80] have presented a technique for microzonation for the city of Armenia in Columbia. In this study, they used a 3D layer model in GIS, combined with a 1D seismic response using SHAKE to get the spatial variation in seismic response which was checked with the damage assessment of Armenia. Topal et al[83] have considered various parameters for microzonation such as geological, geotechnical, seismotectonic and hydrogeological conditions and on the basis of these, four different zones were proposed for the Yeneshir an urban area in Turkey.
Ansal et al[22] adopted a probabilistic approach in a microzonation study for the city of Siliviri, Turkey. Ansal et al[20] developed a seismic microzonation map and assessed damage scenarios of Istanbul, Turkey. Many studies claim microzonation by presenting a map of period of soil column or site response but these are one of the geotechnical parameter in the microzonation. The scale of microzonation map is also important as this depends on the grid size of data cell.

Scale for Microzonation

The local site effects during earthquakes is related to geotechnical characteristics such as amplification, liquefaction, land slide, mudflow and fault displacements. To assess these geotechnical characteristics, three grades of approaches for zonation were suggested by ISSMGE Technical Committee for Geotechnical Earthquake Engineering along with the scales for mapping. The scale of zonation depends mainly on the available database and on the quality of the zonation map required. Several inputs regarding seismicity, geology and geotechnical characteristics are necessary for seismic microzonation of an area.

The microzonation is graded based on the scale of the investigation and details of the study carried out. The technical committee on earthquake geotechnical engineering of the International Society of Soil Mechanics and Geotechnical Engineering (TC4-ISSMGE 1999)[81] states that the first grade (Level I) map can be prepared with scale of 1:1,000,000-1:50,000 and the ground motion was assessed based on the historical earthquakes and existing information of geological and geomorphological maps. If the scale of the mapping is 1:100,000-1:10,000 and ground motion is assessed based on the microtremor and simplified geotechnical studies, then it is called as second grade (Level II) map. In the third grade (Level III) map ground motion has been assessed based on the complete geotechnical investigations and ground response analysis with scale of 1:25,000-1:5000. The recommended grid size for data collection and experimental studies for different level of seismic zonation by TC4 is summarized below:

Level I
Homogeneous sub-surface – 2 km x 2km to 5 km x 5km
Heterogeneous sub-surface – 0.5 km x 0.5 km to 2 km x 2km
Level II
Homogeneous sub-surface – 1 km x 1km to 3 km x 3km
Heterogeneous sub-surface – 0.5 km x 0.5 km to 1 km x 1km
Level III
Homogeneous sub-surface – 0.5 km x 0.5km to 2 km x 2km
Heterogeneous sub-surface – 0.1 km x 0.1 km to 0.5 km x 0.5km

The above recommendation may be suitable for heterogeneous sub-surface if the region is free from any infrastructure. Data points for each grid size can be selected based on field feasibility and data type. If the old borehole data are collected, then maximum possible data can be collected and used for the study. If geophysical experimental is planned, at least a minimum of one geophysical data can be collected for grid size of 0.5 km x 0.5 km to 2 km x 2 km. These results have to be verified randomly by comparing with borehole data and other means. Microzonation studies have to be carried out at a possible smaller scale i.e. 1:5,000 to 1:20,000 with larger number of data points rather than three levels.

Seismic Microzonation Methodology

Many earthquakes in the past have left many lessons to be learnt which are very essential to plan infrastructure and even mitigate such calamities in the future. Asia is the worst affected continent due to earthquake related damages. The world's costliest natural disaster was reported as Japan Earthquake March 11th 2011 and Tsunami[88]. India has been facing threat from earthquakes since ancient times in the form of site effects, liquefaction, Tsunami and landslide. But still seismic zonation and microzonation are in the sapling stage in India. Many studies used existing model and methodology proposed for other regions which have provided reasonably comparable results in some cases but many times lead to wrong results. Methodology has been developed for seismic zonation. This methodology is framed by considering experiences gained from Bangalore microzonation study[18] and by reviewing others similar works.

This methodology may be used for any other region as this methodology does not compose of any regional parameters. Seismic zonation is composed of the following four main phases. In the first phase, the earthquake source characterization for the study area needs to be determined more accurately with seismotectonic map. This can be used for deterministic and probabilistic analysis to map the required parameters at rock level. In the second phase, a detailed site characterization has to be carried out using geological, geomorphological and geophysical and geotechnical data. It should also help in considering other relevant factors like topographical and basin effects, soil nonlinearity etc. This is very essential for the assessment of site dependent seismic hazard parameters.

In the third phase, analysis and interpretation of the accumulated data in the above two stages can be used in detailed estimation of site specific effects which includes site amplification, liquefaction, landslide, Tsunami etc. These analysis could be utilized for urban planning and thus for earthquake risk mitigation purposes. Finally the seismic zonation map with the accepted scales can be prepared with respect to the required seismic hazard parameters.

This methodology can be used for any level of study but the parameters remain same. If the scale is small, then developed map can be called as microzonation map and if the scale is large, map can be called as macrozonation map. Macrozonation map can be produced for district, state and country, where the data grid is more than 5 km x 5 km in size and microzonation map can be produced for city, where the data grid point is less than 1 km x 1 km. New seismic zonation/microzonation steps with possible seismic hazard parameters are shown in figure 1a and 1b. Newly proposed steps clearly show the possible input data, analysis and output results and then how output in each step can be used as input for subsequently steps. Default in one step will affect the whole microzonation results/maps, so careful evaluation of each step is mandatory. This methodology takes into account geology, seismology, seismotectonics, deep geophysical data, geotechnical aspects of site effects, liquefaction, landslide and tsunami hazards.

The first step illustrates the assessment of the expected ground motion using the deterministic and probabilistic seismic hazard analysis. The site characterized for the study area at possible scale using geotechnical and shallow subsurface geophysical data is covered in the next step. Third step is the study of local site effects using first and second step output data and estimating ground level hazard parameter. Fourth step is the assessment of liquefaction potential considering the site amplification and soil properties. Fifth step is the landslide hazard assessment valid for hilly terrains/cut and fill area only. Sixth step is Tsunami hazard mapping which is needed for coastal regions only.

The final step is integration of all the above maps by assigning proper ranks and weights based on the importance of each hazard parameters to prepare the final macro or micro zonation map of a region. Final map of the region can be used to identify highly hazardous area where seismic risk and vulnerability studies have to be carried out. All these maps are complied on GIS platform by incorporating all spatial parameters in the city/urban centre, so that this can be effectively used for identification of high hazard area, city planning, construction and retrofitting work, disaster management and post event relief work planning.

Methodology for Seismic Hazard Analysis

Seismic hazard of any region plays most important role in microzonation. To estimate bed rock seismic hazard, deterministic and probabilistic approach are widely used. Steps discussed by Kramer[59] can be followed for deterministic and probabilistic hazard analysis. Major component of seismic hazard analysis is identification of existing seismic sources and earthquake event compilation and characterization i.e. collection of seismotectonic parameters and preparation seismotectonic map. The seismotectonic map should consist of the geology, geomorphology, water features, faults, lineaments, shear zone and past earthquake events around the study area. If the region has moderate seismic history, plate terrain and far away from the sea, then seismotectonic map covering an area of 300 km to 700 km radius around the study region will be sufficient. If the region is very close to sea, within 2000 km from major plate boundaries and history of major earthquakes, then seismotectonic map should be prepared for 2000 km to 5000 km radius around the study area.

Seismic hazard parameters such as peak ground acceleration, spectral acceleration and acceleration time histories are determined in seismic hazard analysis using regional seismotectonic parameters and should be mapped in GIS platform. While carrying out seismic hazard analysis, one should carefully estimate regional recurrence relation, maximum possible magnitude, seismic source parameters and selection of proper predictive relation and source models. Here one should also remember that conventionally followed seismic hazard analysis depends on the past earthquake history of the region. These approaches may not yield good results about maximum possible magnitude, location and seismic hazard parameters for future earthquake in the region of poor seismicity data. To handle lack of proper past seismic data and source details, Anbazhagan et al[8] proposed ruptured based seismic hazard analysis for the future zonation. The authors have shown the difference between the conventional deterministic approaches with new rupture based approach. Rupture based seismic hazard analysis by Anbazhagan et al[8] may be an effective seismic hazard analyses for microzonation because frequent updates are mandatory for every 20 years.

Methodology for Site Characterization

Seismic hazard analysis gives seismic hazard parameters at bedrock level. But damages due to seismic activities also depend up the site specific properties of subsurface materials that exist below the surface and up to hard rock. Site characterization is a process of classifying region/ site considering average subsurface material properties. Site classification is a more direct indicator of local site effects. In the initial stage of seismic microzonation, surface geology was used for site classification, but later it was proved that considering the geological units as the only criteria for seismic site characterization is not appropriate.[21]

Wills and Silva[87] have suggested shear wave velocity for seismic site characterization rather than geological units despite the determination of shear wave velocities requiring extensive field investigations. Seismic site characterizations are inevitably reflected in modern seismic code provisions to account for site effects. Modern seismic codes in America, Europe, Japan and worldwide [International building code (IBC 2009)[46], Unified Building code (UBC 1997)[84], National Earthquake Hazards Reduction Program (NEHRP, BSSC, 2003) [31] and EC8[37], 2007] have produced numerous valuable information based on experimental and theoretical results.

Table 1 shows the summary of site classes adopted in NEHRP (BSSC, 2003)[31], IBC[46] (2009) or UBC[84] (1997) and EC8[37] (2007). In order to avoid confusion of detailed specifications, only key information is given in table 1 for direct comparison. In recent times, many studies have presented site classification using geotechnical and geophysical field studies for seismic microzonation.

Some of them are using only shear wave velocity (SWV) for site characterization. SWV measured using geophysical techniques by Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) or estimated from the existing correlation between SPT N and SWV are widely used. Studies show that using SPT N or SWV from N gives stiffer site class than site class based on measured SWV for medium to dense soil sites with shallow engineering bedrock.[9,11,12] Site classification considering only SWV with limited knowledge about soil lithology may yield wrong site class. Comprehensive site classification considering SWV and random comparison and correlation with drilled borehole data with SPT N values will give appreciable results. Simple steps for site classification are given in figure 2.

Researchers should also be aware about the conventional site classifications given in table 1 which were developed based on detailed regional study and local soil type. Following these classification systems in Asia result in stiffer site class and lower spectral values when rock depth is less than 25 m and vice versa for the soil exceeding more than 40 m.[11,12] Many researchers have raised doubts about validity of Vs[30] for site classification and soil amplifications in tectonically active regions[32,51,52,61,86]. Current practice of using SWV and SPT N up to 30 m does not account for proper soil thickness and layering as these are limitedly obtained from SWV and SPT N test methods. Some geophysical methods such as ground penetrating radar (GPR) and resistivity surveys may be used to delineate rock depth and soil layers with underground buried objects.

It is also noted here that geotechnical provisions given in major Asian (China, Indian and Australia) earthquake codes are not comparable with the modern seismic codes discussed above[12]. As a part of site characterization, dynamic behavior i.e. variation of shear modulus and damping with strain (called as reduction curves) has to be evaluated. If it is not possible to evaluate them due to lack of resources, one can use index properties obtained from the boring test to group the soil layers and select exiting reduction curves. Many reduction curves developed by researchers are available in the site response software of SHAKE2000. These curves have been selected carefully and may be validated by carrying out few test studies. Studies have shown that the selection of slightly different reduction curve for similar materials can yield in similar amplification and response spectrum.

Site Specific Response Analysis

The next important step in the microzonation study is site specific response analysis. The main objective of this study is to find out site response parameters such as period of soil column, amplification and response spectrum using site specific dynamic properties. Data and results arrived from the seismic hazard analysis and site characterizations are utilized in this part. Typical site response steps are given in figure 3. Site response parameters can be calculated experimentally using recorded strong motion data or weak motion data and numerically using wave propagation theories. Site response parameters can also be estimated using available empirical correlations based on experimental studies in the literature and site specific response studies.

Empirical relation developed to estimate amplification is recommended in National Earthquake Hazards Reduction Program (NEHRP) and summary of these correlations and other correlations are given in Anbazhagan et al.[11] Since the amplification empirical relations are region specific, one should be careful about these empirical relations for microzonation unless otherwise, the equations are matching with regional data. Generations of site specific response/design spectrum procedures are inevitably incorporated in the modern seismic codes of America, Europe, Japan and worldwide (IBC 2009, UBC 97, NEHRP and EC8)[31,37,46,84].

Most of these codes give the design spectrum considering seismicity of the region from the detailed hazard analysis and site class based on 30 m SWV or SPT N as arrived from the site classification. So, the empirical based site response results can be adopted in preliminary studies or some-times to cross validate site response results if measured site response values are limited in the region. Detailed site response analysis is the main focus of ground motion analysis in microzonation, where representative site response parameters are to be mapped.

Site response study of region depends on input ground motions, depth at which ground motion is assigned and soil parameters such as layer thickness, shear modulus (or its correlations) and modulus reduction curves. Regional recorded input motions are always appropriate and if it is not available then suitable input ground motion (GM) can be selected from the globally available ground motion data -base by matching regional seismicity. If it is difficult to find appropriate GM for region by above two approaches, one can synthetically generate ground motion considering seismotectonic parameters[18]. Another important issue is the selection of number of input ground motions used for site response analysis at one location.

Use of number of ground motion data for one location or scaling up one motion is also practiced, if GM data is limited[20]. One GM i.e. most expected earthquake for that location is sufficient for seismic microzonation. Site response studies focus on the development of develop response/design spectrum, then multi GM data can be used for one location and average spectral values can be used to arrive design spectrum. Thickness of soil layers can be obtained from the measured data. If soil layer is having thickness greater than 3 m, then the soil layer should be divided into number of sub layers and used for analysis. If the thickness of same material is more than 3 m, SHAKE analysis predicts higher PGA values. Figure 4 shows typical depth versus peak ground acceleration for thin soil layers (< 3m) and thick soil layer (> 3 m) for same site, other parameters remain the same for both the cases.

More details on the effect of soil layer thickness can be found in Anbazhagan et al[4]. Shear modulus (G_{max}) of subsurface layer is estimated from measured shear wave velocity (SWV) and SPT N values. Density of soil layers can be measured and used for G_{max} estimation, otherwise the range density for different SWV given by Kokusho[51] can be also adopted. When the SPT N values are used to estimate G_{max}, one should be aware of the details of existing correlation and its suitability for that region[17]. Proper selection of modulus and damping reduction curves for soil layers are mandatory for the prediction of accurate site response parameters, even though small change in modulus curves does not affect final results. One dimensional equivalent linear site response analysis is widely recommended for microzonation, however cross verification using the following models at selected locations is highly recommended.

1) Non linear site response study
2) Two or Three dimensional site response for heterogonous soil layers and highly different elevation levels to account topographical effects

Liquefaction hazard mapping

The significant amount of cumulative deformation or liquefaction has been one of the major concerns for geotechnical engineers. Liquefaction and related deformation can be expected even without undergoing modification of seismic waves. Liquefaction can occur in moderate to large size earthquakes i.e. $M_W > 4.6$[44,74] which can cause severe damages to structures. Transformation of a granular material from solid state to liquid state due to increased pore pressure and reduced effective stress is defined as liquefaction[57]. When this happens, the sand grains lose its effective shear strength and will behave more like a fluid. The grain size distribution of soil, duration of motion, amplitude and frequency of shaking, distance from epicenter, location of water table, cohesion of the soil and permeability of the layer can affect liquefaction potential of any soil. The liquefaction hazards are associated with saturated sandy and silty soils of low plasticity and density.

Liquefaction hazard map is important to identify vulnerable areas as these hazards are directly related to ground failure. The liquefaction potential of soil is generally estimated from laboratory tests or field tests. Among the many field in-situ tests, SPT test and shear wave velocity test are widely used for liquefaction evaluation purpose. Liquefaction potential of site can be assessed by following sequence of steps:

1) Liquefaction Susceptibility Mapping
2) Factor of Safety against Liquefaction Assessment
3) Depth or zone of Liquefaction
4) Liquefaction Potential Index
5) Liquefaction Severity Index
6) Ground Deformation due to Liquefaction

Liquefaction ‘susceptibility’ is a measure of a soil’s inherent resistance to liquefaction and can range from not susceptible, regardless of seismic loading, to highly susceptible, which means that very little seismic energy is required to induce liquefaction. Susceptibility has been evolved by comparing the properties of top 20 m soil deposits in the site to the other soil deposits where liquefaction has been observed in the past[73]. More details of liquefaction susceptibility mapping can be found in work of Sitharam et al.[76] After successful identification of liquefaction susceptible area, other steps of 2 to 6 can be followed depending upon requirement. Factor of safety against liquefaction has been usually estimated in the microzonation studies by considering worst scenario earthquake.

Factor of safety against liquefaction of soil layer can be evaluated based on the simplified procedure[71] and subsequent revisions of the simplified procedures[33,72,73,89,90]. There are two parameters subsequently evaluated before the calculation of factor of safety against liquefaction which are Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR). CSR represents the earthquake loading and is evaluated in terms of equivalent cyclic shear stress amplitude considering peak ground surface acceleration (PGSA) of earthquake, total and effective vertical stresses of soil layer and stress reduction coefficient (r_d). CRR represents liquefaction resistance of soil, which depends on how close the initial state of soil is to the state corresponding “failure”. CRR values are widely arrived considering corrected SPT “N” value or shear wave velocity using a chart proposed by Seed et al[73], Youd et al[90], Cetin et al[33] and Idriss and Boulanger[47]. These CRR values are for the earthquake moment magnitude 7.5, for other magnitudes CRR should be corrected by magnitude scaling factors (MSF). Typical steps involved for calculation of factor of safety against liquefaction are given in figure 5.

The detailed procedure and discussion on CSR, PGSA, r_d, CRR and MSF with typical calculation can be found in Anbazhagan[13]. The probabilistic approach has also emerged recently in liquefaction evaluation which gives factor of safety against liquefaction in specified depth and required SPT N values to prevent the liquefaction.[85] Soon after the earthquake, the soil gets densified and this will appear at the ground surface in the form of settlement. The settlement of dry sand will be complete once the earthquake is over. However in the case of saturated soils, the duration of settlement will be more and it will continue till the excess pore pressure generated due to the earthquake is fully dissipated. This dissipation of pore water pressure depends on density of sand, induced shear strain and the excess pore water pressure developed during the earthquake. The empirical curves developed by Tokimatsu and Seed[82] for prediction of ground subsidence after liquefaction is widely used. These curves give the volumetric strain values as a function of corrected SPT and CSR values. Ishihara and Yoshimine[48] have also developed experimental charts for the prediction of liquefaction induced settlement.

In this work, the settlement was modeled as a function of factor of safety against liquefaction, corrected SPT and CPT values and the CSR value. The lateral displacement caused due to liquefaction has been a major liquefaction related topic due to its huge impact on the buried structures. Lot of research work is being carried out on this topic due to its impact on the buried under-ground structures. Bartlett and Youd[26,27] have proposed a relation to estimate the lateral ground displacement further modified by incorporating more data by Youd et al[89]. All liquefaction related studies have originated from the simplified procedures of Seed and Idriss[71] and factor of safety against liquefaction is essential part for any liquefaction analysis. Liquefaction hazard mapping using different procedure and comparison is presented by Anbazhagan[13].

Landslide Hazard Mapping

Earthquakes can activate slope failures in undulating terrains leading to landslides with catastrophic post effects. These depend on several factors inherent to the soil conditions such as geology, hydro-geology, topography and slope stability. Landslide hazard mapping is mandatory for region in the foot hills and undulation terrain or close to these. Landslide induced by earthquake is region specific and hence it is not evaluated together with conventional microzonation parameters. But it is the duty of microzonation experts to decide requirement of landslide studies for a particular region. Landslides are complex natural phenomena that are hard to model and simulate.

Predicting hazardous events like landslides are particularly difficult because no laboratory tests can preliminarily measure the necessary variables, refine the techniques and apply the results.[35] Mitigation of disasters due to landslides can be successful only with detailed knowledge about the expected frequency, character and magnitude of mass movements in an area. Hence, the identification of landslide-prone regions is essential for carrying out quicker and safer mitigation programs as well as for the future strategic planning of an area.

Therefore, the Landslide Hazard Zonation (LHZ) of an area becomes important whereby the area is classified into different LHZ ranging from very low hazard zone to very high hazard zone[24]. Landslide susceptibility mapping is of great value for landslide hazard mitigation efforts[38]. Landslide hazard analysis focuses mainly on the spatial zoning of the hazard[28]. The zonation of landslide hazard is defined in four category i.e. “nil or low”, “moderate”, “high” and “very high. This can be achieved through simplistic analysis based on the preparatory factors of soil and slope conditions, seismicity, water content, rainfall etc. by carrying out pseudo-static analysis or detailed finite-element method considering nonlinear behavior of the soil response.

Susceptibility analysis for predicting earthquake-induced landslides has been done using deterministic methods. Multivariate statistical methods have not previously been applied for deterministic analysis. A statistical methodology that uses the intensity of earthquake shaking as a landslide triggering factor was introduced first. This methodology is applied in a study of shallow earthquake induced landslides in central western Taiwan. 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[41], Hungr[45] and Perkins[66].

The advanced techniques were recently proposed by several researchers like Jibson et al[50] and Del Gaudio et al[36]. These are inherently rigorous with extensive data inputs comprising of triggered landslides inventory. The parameters considered are strong-motion records, geological maps, engineering properties, digital elevation models of the topography and employs dynamic model based on Newmark’s permanent deformation (sliding block) analysis. This method was developed and used for zoning of slope failure susceptibility in Kanagawa Prefecture, Japan (Kanagawa Prefectural Government, 1986) based on slope failures during three large earthquakes in Japan.

Tsunami Hazard Mapping

Tsunami is a series of waves with long wavelength and period (time between crests) which can vary from a few minutes to over an hour. Tsunami is generated by any large, impulsive displacement of the sea bed level. Earthquakes generate tsunamis by vertical movement of the sea floor. If the sea floor movement is horizontal, a tsunami cannot be generated. Earthquakes with $M_w > 6.5$ are critical for tsunami generation. Tsunamis can also be triggered by landslides into or under the water surface and also by volcanic activity and meteorite impacts. On an average, there are two tsunamis per year somewhere in the world which cause damage near the source. Approximately every 15 years a destructive, pacific-wide tsunami occurs.

Tsunamis are among the most destructive coastal hazards and it was witnessed in the Indian Ocean on 26 December 2004, in which a single event can cause loss of life of the order of 3,00,000 and damage of several billion US dollars[64]. It is evidenced that Tsunami in Japan due to March 11th 2011 earthquake damaged structures designed against earthquakes. Considering Tsunami hazard is mandatory for the microzonation of region close to sea. But most of cases Tsunami hazard assessment is usually not coupled with seismic microzonation.

The main reason for potential loss due to Tsunami is unpreparedness and unawareness about the Tsunami in the coastal regions because of very large return period. So unpredictable damages and human loss in the coastal region can be minimized if knowledge of Tsunami run-up and inundation studies are available. Also these results are useful to plan Tsunami warning system in coastal cities.

The following simple steps can be followed to map Tsunami run-up and inundation area:

1) Collection of seismic information such as past earthquake in the coastal regions, earthquake sources and tsunami records using literatures in and around the study area.
2) Preparation of Tsunamigenic sources map for study area.
3) Estimation of maximum probable potential earthquake produced by each Tsunamigenic sources.
4) Estimation of source parameters for maximum Tsunamigenic earthquake.
5) Tsunami hazard analysis and determination of probable Tsunami generation in near future.
6) Tsunami run-up estimation for probable Tsunami with modeling sea and land floor terrain.
7) Mapping of Tsunami Inundation area for probable Tsunami waves.
8) Mapping Tsunami hazard area based on probable Tsunami for maximum Tsunamigenic earthquake for region.

Many Tsunami assessment models are available for free in the WebPages after Indian Ocean Tsunami on December 26th, 2004. Proper models can be selected based on available data used to map tsunami hazard.

After assessing each parameter listed in figure 1, these have to be complied with proper weights and ranks for final hazard index mapping for disaster management. Microzonation maps should be prepared in GIS platform where all city information's are created as GIS layers so that these maps can be further used for seismic vulnerability and risk analysis. These are essential for disaster planning and management of urban centers. Microzonation mapping in GIS platform is presented by Anbazhagan et al[18].

Seismic Microzonation Practices

Seismic microzonation studies are carried out in many countries where there is no detailed ground condition based of seismic hazard mapping and inadequate seismic standards. Microzonation studies were conducted in few earthquake prone areas of the world by Marcellini et al[56], Chavez-Garcia and Cuenca[34], Lungu et al[54], Faccioli and Pessina,[39] Slob et al[80], Fäh et al[40], Alfaro et al[2], Topal et al[83], Ansal et al[19], Ansal et al[20] etc.

Most of these microzonation studies have concentrated only on hazard analysis and site effects but other parameters are neglected. Site effects based microzonation may help to frame good response/design spectrum, but may not be helpful for disaster management and planning as other hazards parameters are not included in the microzonation mapping. Seismic microzonation mapping is relatively new in Asia, even though many devastating earthquake are frequently reported in Asia. Many Asian cities, in particular Indian cities do not have proper seismic hazard and microzonation maps. Recently India has targeted detailed microzonation studies for 63 cities[79]. Some of them are finished while some of them are ongoing. Seismic hazard analysis and microzonation was taken up for Jabalpur city in Madhaya Pradesh. Further, cities of Sikkim, Mumbai, Delhi, North East India, Gauwhati, Ahmedabad, Bhuj, Dehradun, Chennai, Haldia, Talchir Basin and Bangalore are also microzoned.

The microzonation of Jabalpur was carried out by the national nodal agencies like Geological Survey of India Central Region Nagpur, Indian Metrology Department (IMD) New Delhi, National Geophysical Research Institute (NGRI), Hyderabad, Central Building Research Institute (CBRI), Roorkee and Government Engineering College, Jabalpur.[65] Seismic hazard and preliminary Microzonation of Delhi was attempted by many researchers. Iyengar and Ghosh[49] Rao and Neelima Satyam,[69,70] Mohanty et al[59] contributed in seismic hazard and microzonation of Delhi region. Nath[62] presented seismic hazard and microzonation atlas of the Sikkim-Himalaya. The first level microzonation map of Guwahati was prepared by Baranwal et al[68] and the hazard index map of Guwahati was presented by Nath[63].

The seismic microzonation of Dehradun was carried out by the researchers Anusuya Barua[23], Rajiv Ranjan[68] and Brijesh Gulati[30]. The earthquake risk assessment (ERA) of buildings in Dehradun was carried out using HAZUS program by Brijesh Gulati.[30] First order seismic microzonation of Haldia was presented by Mohanty and Walling[58]. Seismic zonation of Talchir Basin considering macroseismic intensity was presented by Mohanty et al.[60]

The seismic hazard of Mumbai city was estimated by RaghuKanth and Iyengar[67]. The detailed discussion and map with limitation is available in Sitharam et al[75]. The authors have highlighted that most of the microzonation studies in India were carried out with least attention to geotechnical aspects. The results obtained from the recent studies suggest that the geotechnical aspects in the microzonation studies are mandatory, microzonation without geotechnical parameter is meaningless and proper weights should be given to geotechnical parameters. First microzonation map with all possible geotechnical hazards by deterministic approach has been presented by Anbazhagan et al.[18]

Microzonation Case Study

Seismic microzonation of Bangalore was carried out by considering seismological and geotechnical aspects together. A detailed deterministic hazard analysis of the study region has been carried out and PGA map has been generated for maximum credible earthquake by Sitharam et al[76], Sitharam and Anbazhagan[77]. The spatial distribution of the predicted PGA at bedrock level obtained through contouring, PGA exhibits a monotonic trend with the highest value of 0.15 g to the northwest and lowest of 0.10g to the southeast.

Figure 6 shows PGA distribution based on deterministic approach. Probabilistic seismic hazard analysis (PSHA) and parameters for Bangalore, South India have been presented by Anbazhagan et al[10,11]. The rock level PGA map has been generated for 10% probability of exceedance in 50 years corresponding to the return period of 475 years. Figure 7 shows PGA distribution map of study area. The PGA values obtained from the probabilistic approach are comparable to PGA values obtained from deterministic approach[10].

Anbazhagan and Sitharam[16] carried out detailed analysis of Standard Penetration Test (SPT) data collected in the region and prepared soil overburden thickness map of Bangalore. Anbazhagan and Sitharam[14] carried out 55 Multichannel Analysis of Surface Wave (MASW) surveys at important locations in the city and measured shear wave velocities of the region. They also prepared depth versus shear wave velocity (SWV) distribution map for Bangalore and developed correlation between corrected SPT N values and SWV.

These data were further utilized to develop rock depth map of the region by Anbazhagan and Sitharam[7]. Detailed site classification of the region has been carried out using SPT N and SWV separately using NEHRP 30 m based site classification system, major part of study area classified as site class C and B where amplification is relatively lower.

Anbazhagan et al[9] has presented surface level acceleration using site classification and probabilistic approach. SPT and SWV data are separately used to study site effects of region considering synthetic ground motion generated during seismic hazard analysis. Site response parameters of PGA, spectral acceleration, period and frequency of column have been presented in Anbazhagan and Sitharam.[10] Predominate frequency of soil column is also compared with measured predominate frequency obtained from noise survey. Complied information about studies was presented in Anbazhagan and Sitharam[15] and Sitharam and Anbazhagan.[79]

Possible induced effects of Liquefaction have been assessed. Geographical and terrain review clearly shows that possibility of Landslide and Tsunami is very remote. Detailed liquefaction analysis has been carried out using SPT N values from 620 borehole locations. The SPT N values are corrected by applying necessary correction which is further used to estimate factor of safety against liquefaction. The minimum factor of safety from each borehole location has been considered to map the factor of safety against liquefaction potential at every location.

More details about typical parameters, calculations and maps can be found in Anbazhagan[3]. Out of 620 locations, liquefaction analyses indicate that the factor of safety is less than one in only for 4.2% of the total locations.

Factor of safety of 1 to 2 and 2 to 3 each having 14.7% and 12.5% of the total locations respectively, factor of safety of more than 3 is about 68% of the total locations. For about 33% of total locations detailed study is needed using laboratory tests according to Idriss and Boulanger[47] where these soils (silty clay having PI>12) can cause stress reduction during an earthquake. Factor of safety obtained here also matched with factor of safety arrived based on probabilistic evaluation of liquefaction potential.[85]

Liquefaction potential was also evaluated by carrying out cyclic triaxial testing for selected locations in Bangalore[78]. Further, Liquefaction Potential Index and Liquefaction Severity Index have been estimated using factor of safety against liquefaction and mapped for region.[3] All these studies show that the study area is safe against liquefaction but areas having filled up soil and tank beds need more detailed study.

Microzonation mapping of Bangalore

Seismic microzonation is the generic term used for subdividing a region into smaller areas having different potential for hazardous earthquake effects, defining their specific seismic behavior for engineering design and land-use planning. Final hazard index map of study area has been developed using Analytic Hierarchy Process (AHP) on GIS (Geographical Information System) platform so that these maps can be used for future studies of seismic vulnerability and risk assessment which will also fulfill microzonation purpose.

The final microzonation map can be represented in three forms, 1) hazard map, 2) vulnerability map and 3) risk map, because earthquake loss not only depends on the hazards caused by earthquakes, but also on exposure (social wealth) and its vulnerability. Usually hazard map gives the hazard index (HI) based on hazard calculation and site conditions. Vulnerability map gives us the expected degree of losses within a defined area resulting from the occurrence of earthquakes and often expressed on a scale from 0 (no damage) to 1 (full damage).

Vulnerability study includes all the exposure such as man-made facilities that may be under impact from an earthquake. It includes all residential, commercial and industrial buildings, schools, hospitals, roads and railroads, bridges, pipelines, power plants, communication systems and so on. Risk map will be a combination of hazard classes, vulnerability classes and output risk classes. Here only hazard maps are prepared using deterministic and probabilistic results. Hazard index is an integrated factor which depends on weights and ranks parameters used. Discussion about choosing weights and ranks for each hazard parameter can be found in Anbazhagan et al.[18]

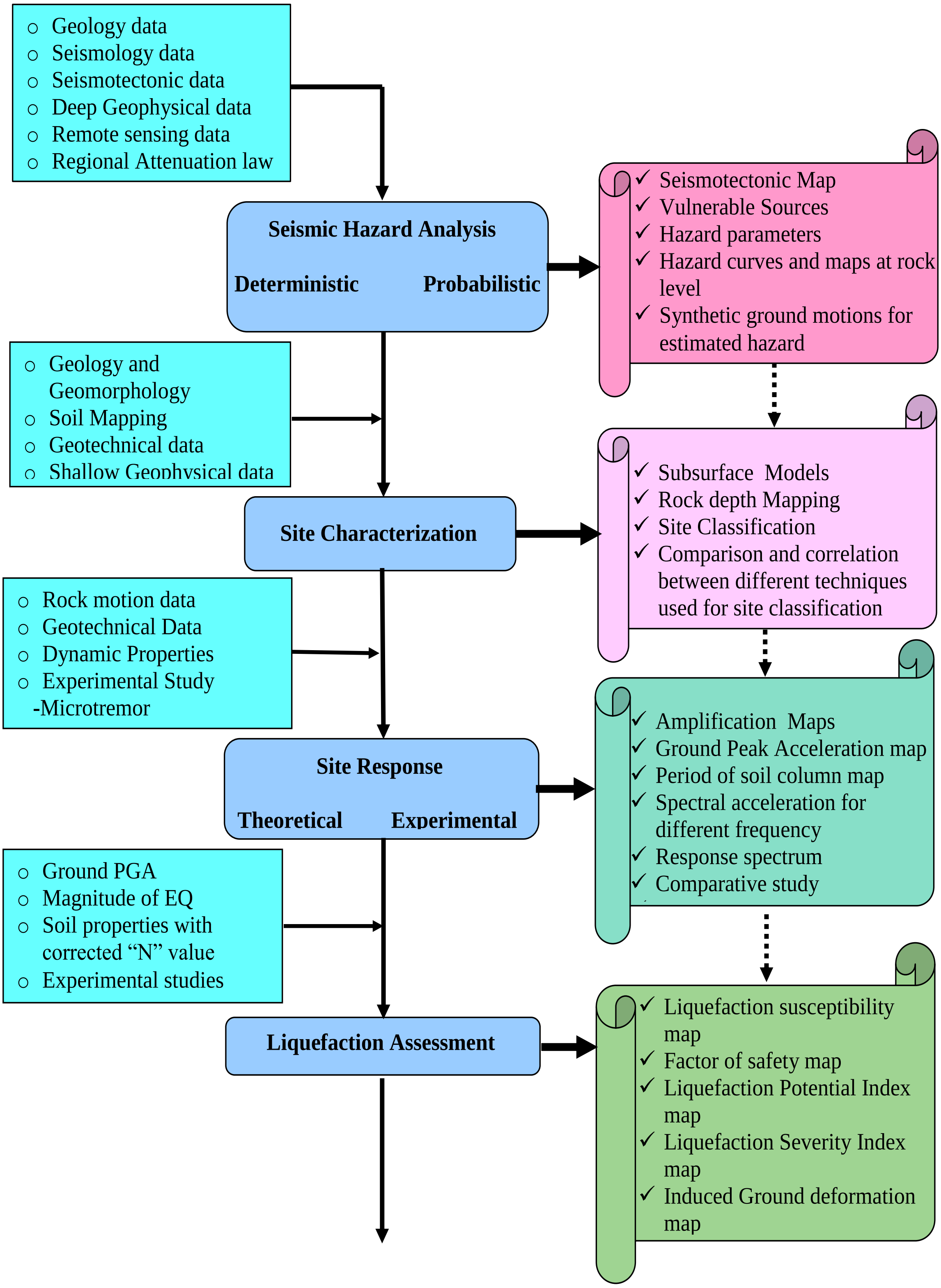

Fig. 1(Part a): Proposed steps for seismic microzonation studies

Deterministic and Probabilistic hazard mapping

Two different seismic hazard maps have been generated, one using deterministic seismic microzonation map based on PGA from DSHA and another is the probabilistic seismic microzonation map based on PGA from PSHA. The major parameters used are PGA at rock level from deterministic and probabilistic approach, site response parameters of amplification and predominant frequency, elevation levels to account topographical variation and factor of safety against liquefaction. In both maps, only rock level PGA is changed and other parameters are kept similar.

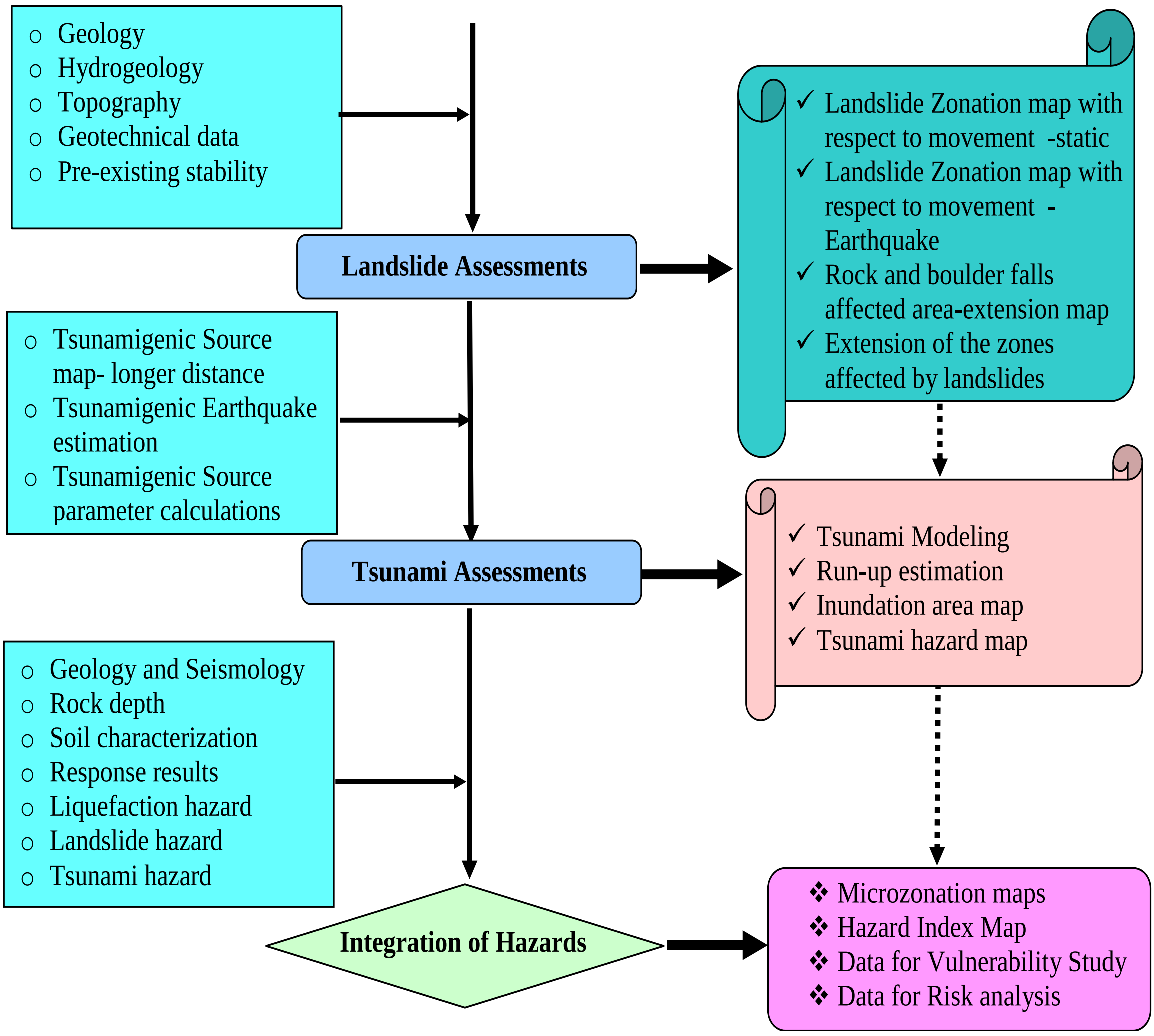

Fig. 1 (Part b): Proposed steps for seismic microzonation studies

Figure 8 shows hazard index map using PGA arrived from deterministic approach, this map is called Deterministic Seismic Microzonation (DSM) map. The maximum hazard is attached to the seismic hazard index greater at central and western part of Bangalore. Eastern part of the city is attached to a minimum hazard when compared to other areas. Southern part has mixed hazard and northern part has moderate hazard. Figure 9 shows hazard index map using PGA arrived from probabilistic approach, this map is called Probabilistic Seismic Microzonation (PSM) map. The maximum hazard is attached to the seismic hazard index greater at south western part of Bangalore. Lower part (south) of Bangalore is identified as moderate to maximum hazard occurrence part when compared to the northern part. Maximum hazard covered by DSM is larger when compared to PSM. According to DSM results, western part of city has maximum hazard and from PSM, southern part of city has maximum hazard.

Comparison of hazard maps by varying hazard parameter shows that final map is influenced on other parameters. In this study, it clearly shows that hazard index distributions are different from PGA distribution based on soil condition and earthquake effects (geotechnical attribution). Geotechnical parameters have to be incorporated in proper weights and ranks in seismic microzonation. These seismic microzonation hazard maps contain important information for the city and regional planning, considering different earthquake hazards. However for important structures a detailed site specific study is needed to be performed at each site during the design stage to evaluate the local site conditions. On the other hand, site specific studies, including in-situ and laboratory tests, must be obligatory in the assessment of required parameters for the structures with higher importance levels.

Conclusion

Essence of seismic microzonation has been presented in this paper with detailed steps for each parameter. It can be seen that most of the microzonation studies were focused only on hazard analysis and site effects without giving due attention to the geotechnical aspects. A case study of Microzonation of Bangalore with possible hazard parameters is presented. Seismic microzonation map based on deterministic and probabilistic hazard analysis has been developed. Variation may be attributed to PGA distribution i.e. seismological parameters, as other parameters are common for both maps. But this distribution does not follow PGA distribution obtained from deterministic and probabilistic approach.

A detailed analysis should be performed to understand the influence of probabilistic based amplification and liquefaction versus site specific amplification and liquefaction parameters which are not focused so far. Many seismic microzonation maps were developed in Asia with limited geotechnical information. The study shows that hazard indices are completely different from seismological hazard parameter distribution. Geotechnical parameters of site effects and induced effects can change hazard index values and distribution. Hence site specific geotechnical aspects are mandatory for seismic microzonation.

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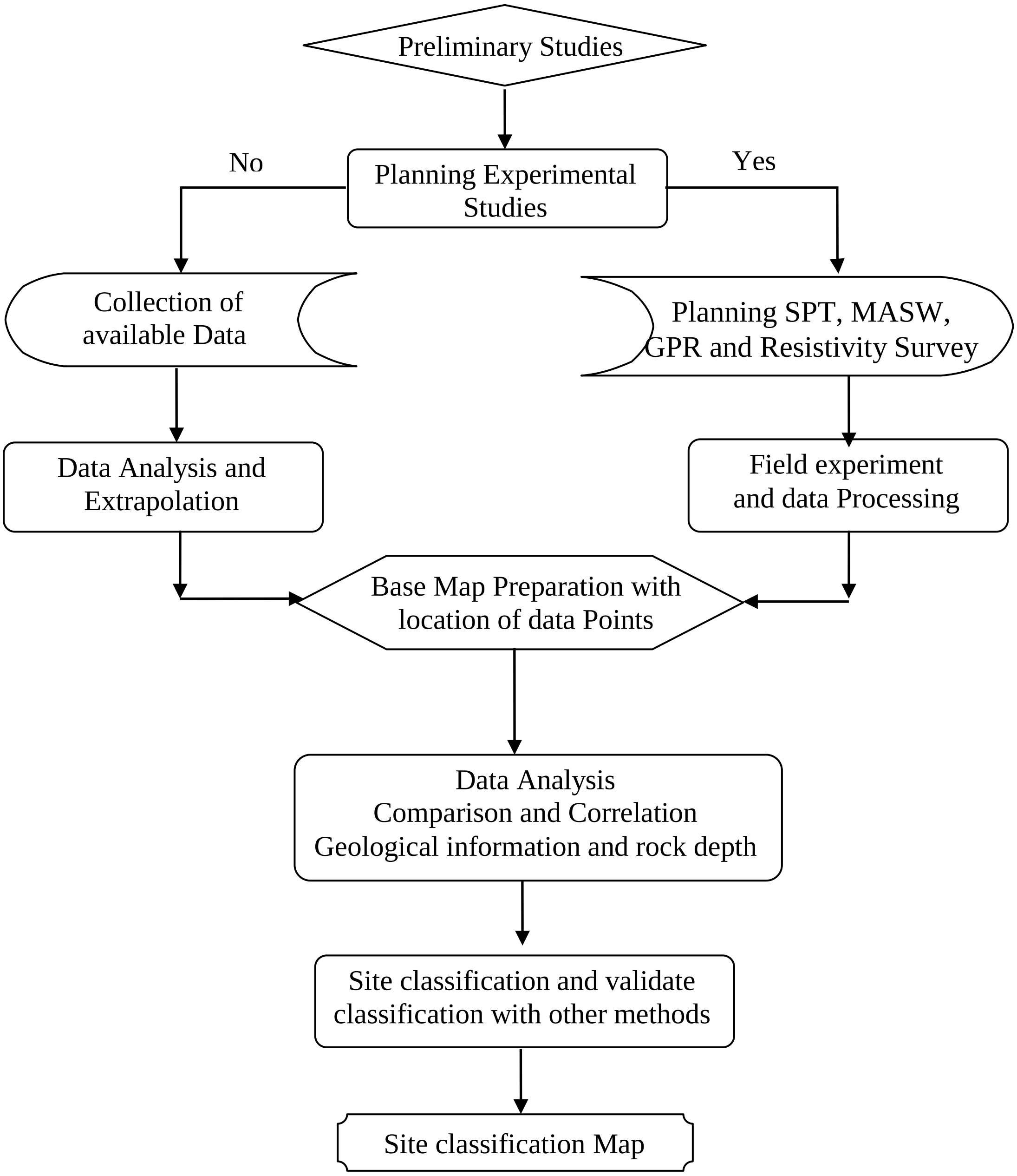

Figure 2: Steps involved for site characterization

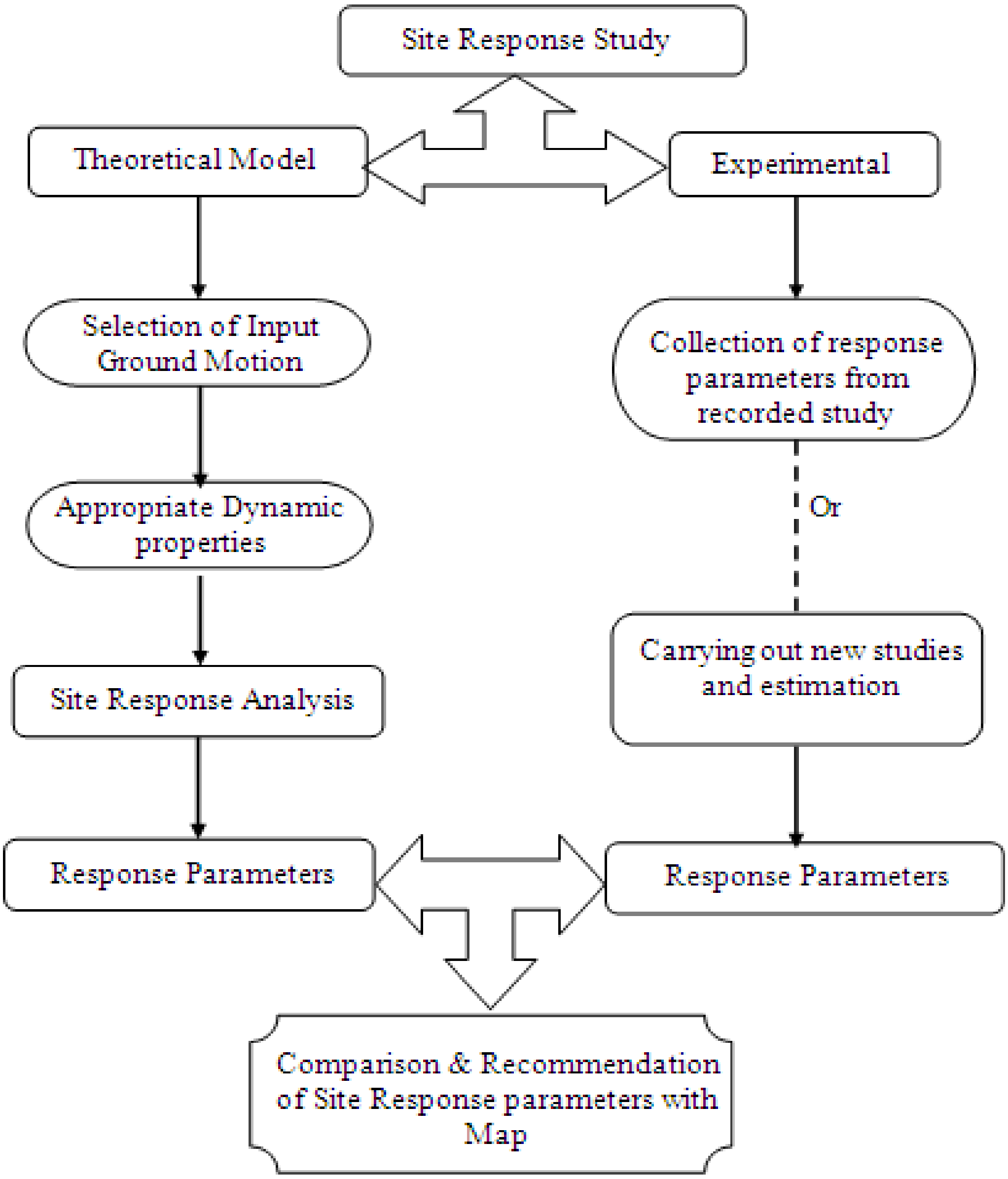

Figure 3: Steps for site response study

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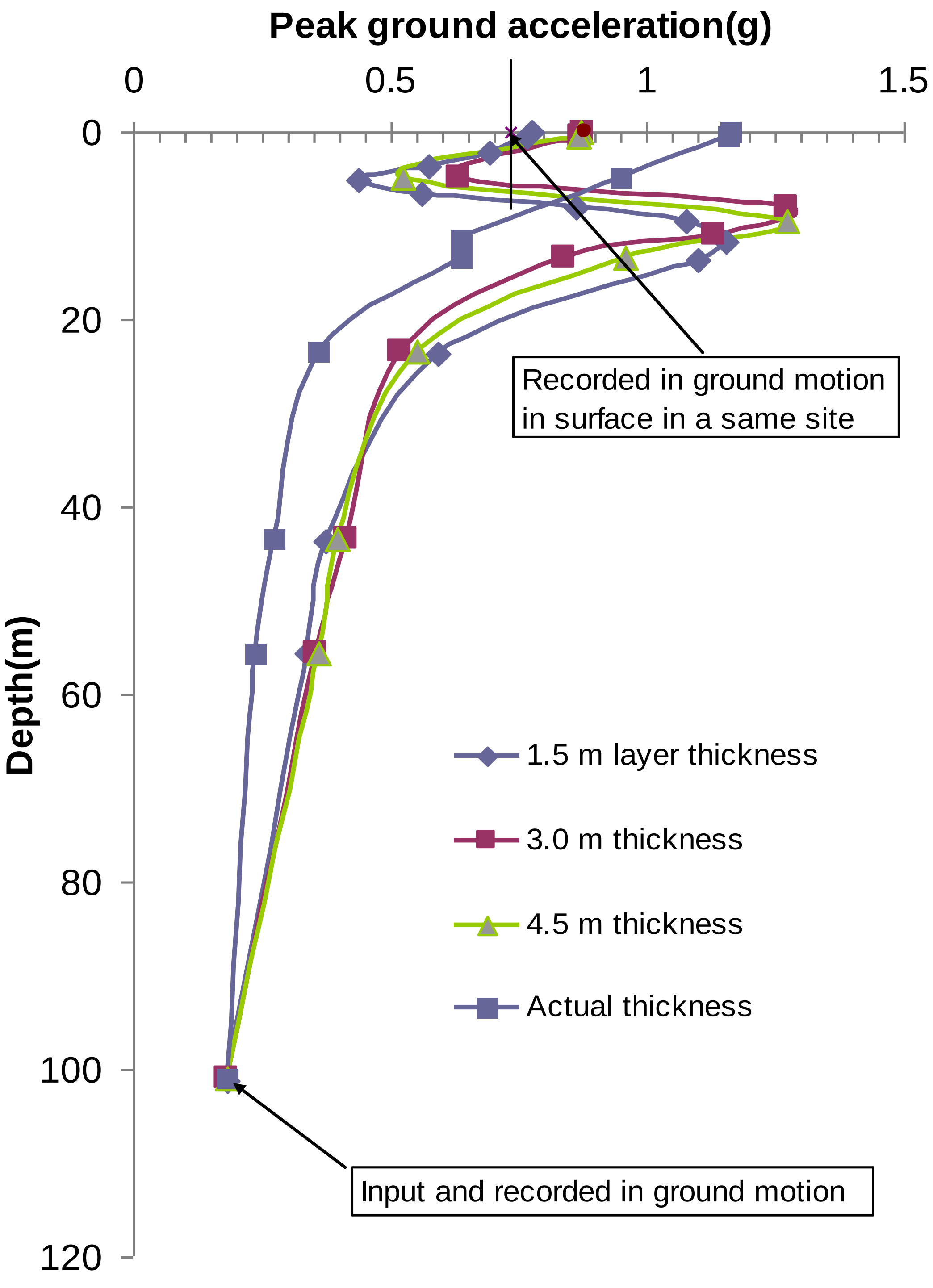

Figure 4: Effects of soil layer thickness in site response study

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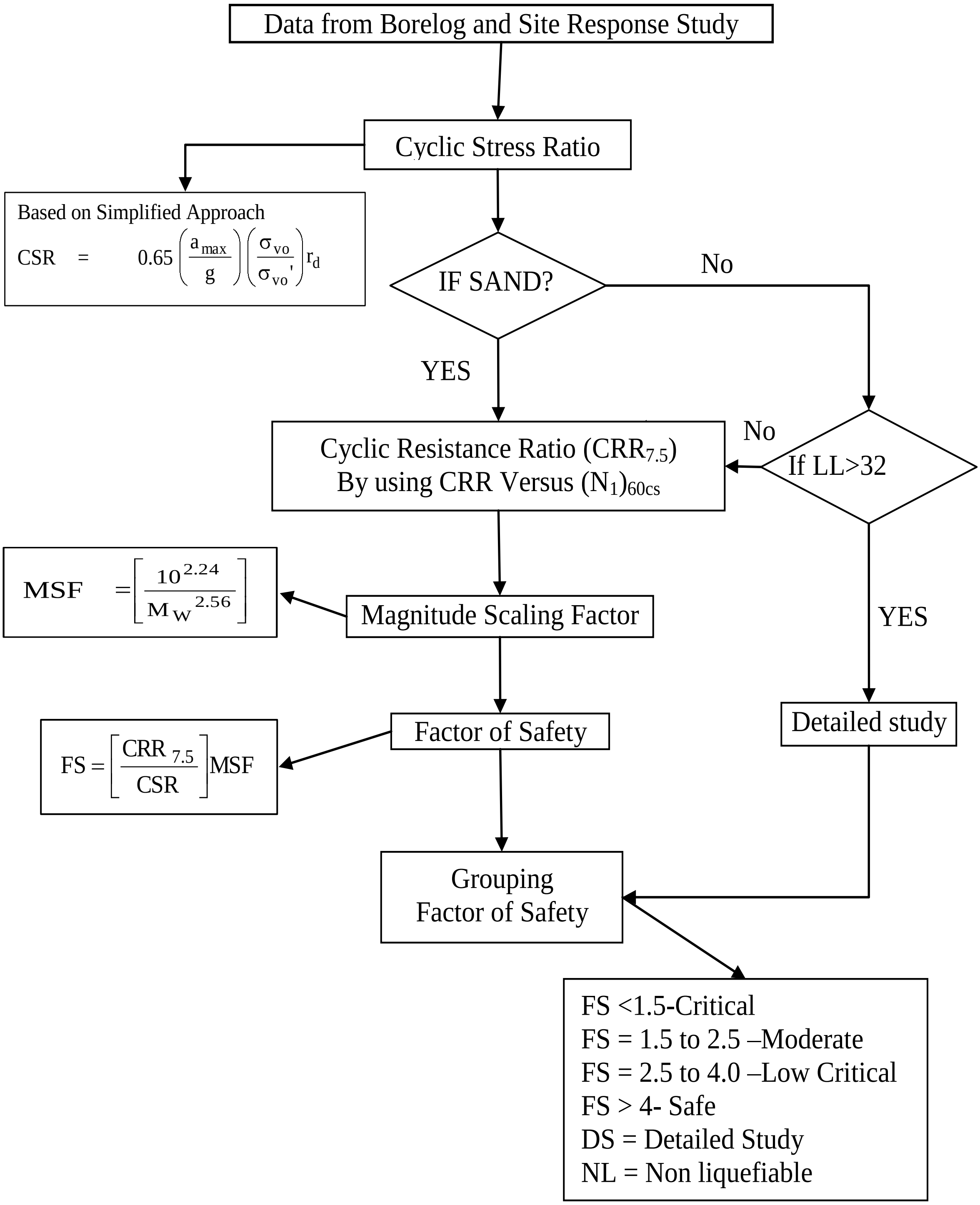

Figure 5: Steps involved in arriving factor safety against liquefaction

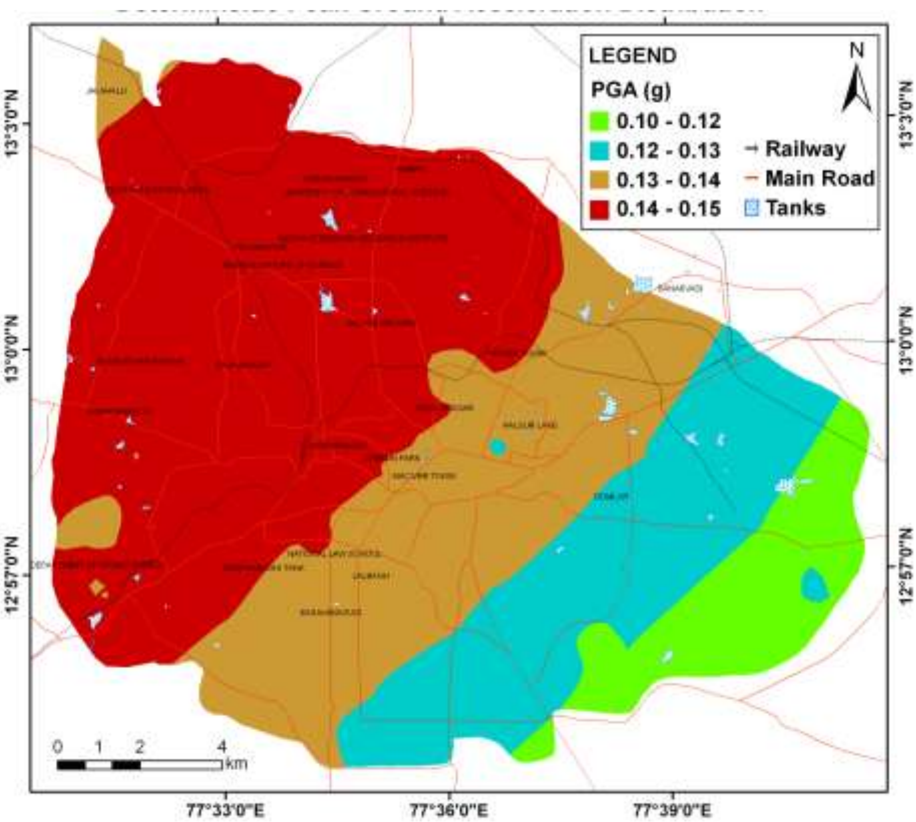

Figure 6: PGA distribution based on deterministic approach[14,15]

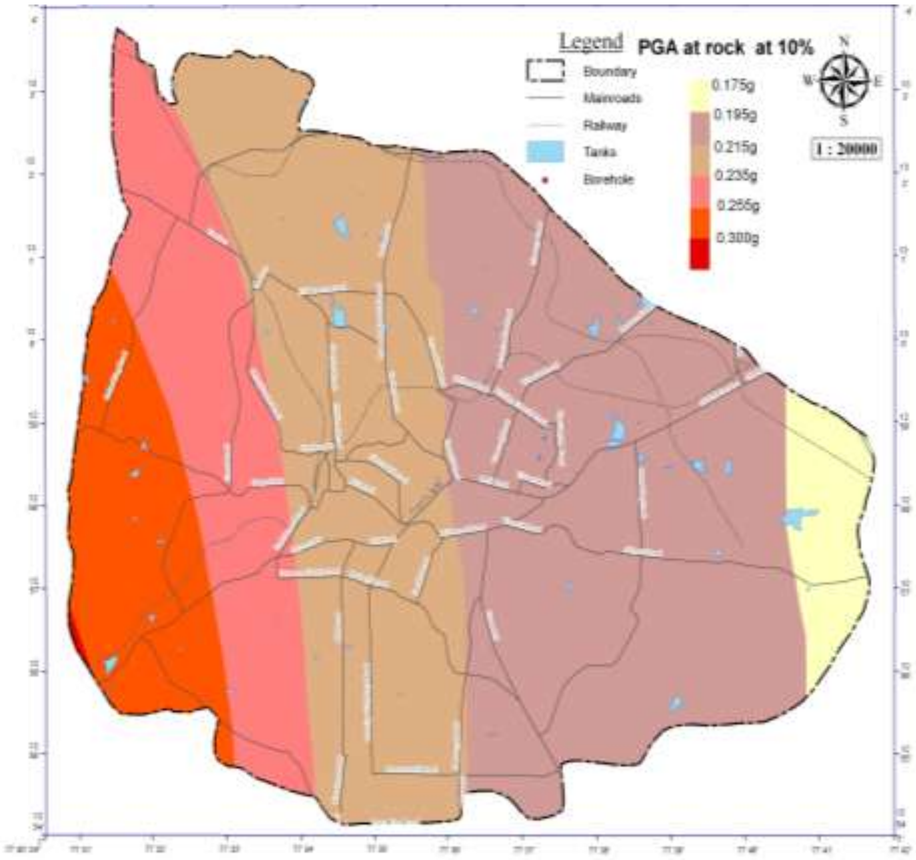

Figure 7: PGA distribution based on probabilistic approach[9]

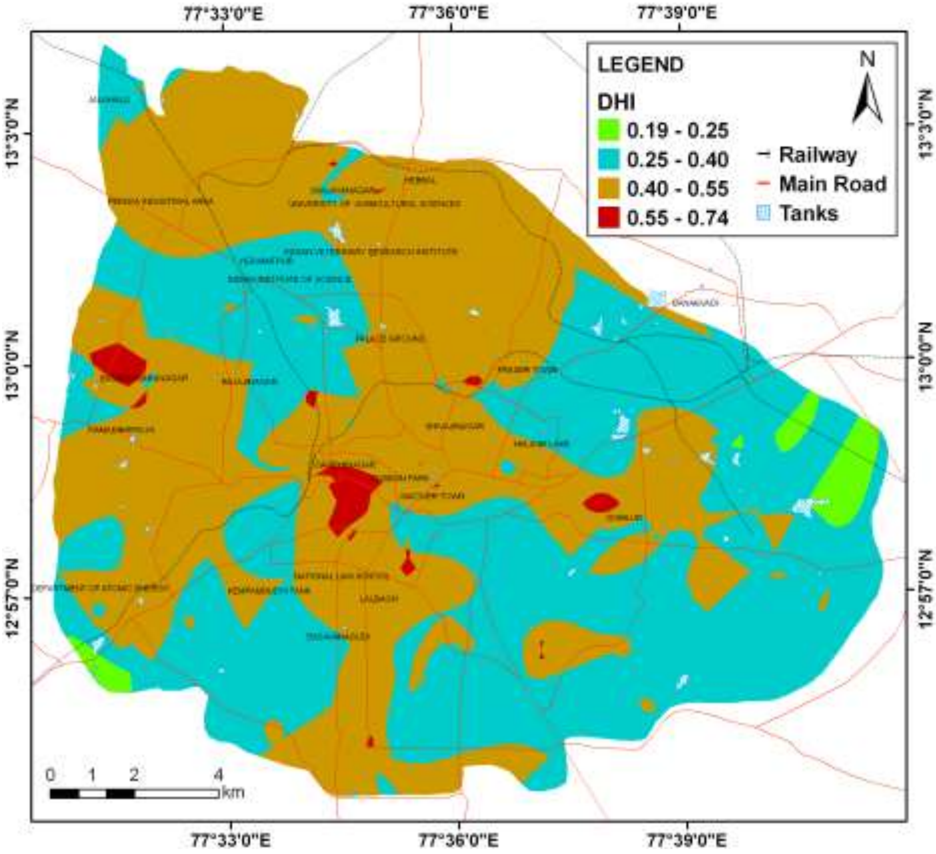

Figure 8: Deterministic seismic microzonation map

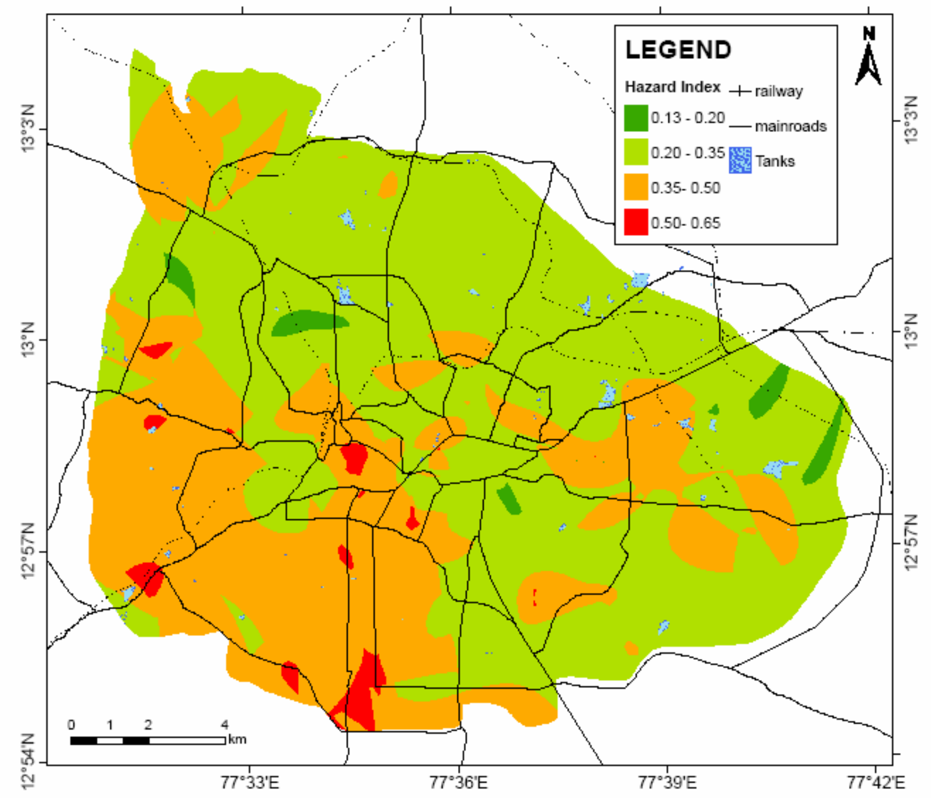

Figure 9: Probabilistic seismic microzonation map

Table 1
Site classification system given in modern seismic codes with Indian Standards

Site Class	**Generalized Description**	**NEHRP (BSSC,2003)**		**IBC 2009/ UBC1997**		**Eurocode 8 (2007)[$]**		**Indian Standards IS 1893 (BIS 2002)**	
		N_{30}	**Vs^{30}**	**N_{30}**	**Vs^{30}**	**N_{30}**	**Vs^{30}**	**N**	**Vs^{30}**
A	Hard rock	N/A	>1500	N/A	>1524	N/A	N/A	*	*
B	Rock	N/A	760-1500	N/A	762-1524		>800	*	*
C	Very dense soil and soft rock	> 50	360-760	> 50	366-762	>50	360-800	>30	*
D	Dense to medium soils	15-50	180-360	15-50	183-366	15 - 50	180 - 360	All the soil 10 to 30 or Sand with little fines N>15	*
E	Medium to soft soil	< 15	< 180	< 15	< 183	<15	<180	<10	*

N/A-Not applicable, * Not mention, [$]The site classes B, C, D and E in this table correspond to site classes A, B, C and D as per Eurocode 8

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