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A Critical Review of Seismic Microzonation Techniques and Applications

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Abstract

It is critical to understand and mitigate seismic risks in seismically active places through seismic microzonation at the global level. The purpose of this review paper is to provide a comprehensive analysis of seismic microzonation efforts around the world, with a particular focus on Indian practices. By incorporating this information into building codes and retrofitting strategies, the built environment can be made less vulnerable to earthquakes. The first section outlines seismic microzonation's work completed in assessing earthquake risks globally. Geophysical, geotechnical, and geological approaches are discussed in the study of seismic microzonation. In addition, tectonic settings, geological features, and ground motion characteristics are discussed in relation to seismic microzonation. In the second section of the paper, seismic microzonation in India is discussed. Because of its diverse geological and tectonic features, India poses a significant seismic hazard. Lastly, the last section discusses the policy implications and practical applications of seismic microzonation in urban planning and disaster management. The study highlights the importance of seismic microzonation and its benefits in improving seismic resilience of India. It also emphasizes the need for further research in this area to better understand the seismic risk in Indian cities.

Keywords: Seismic Microzonation, Earthquake, Shear wave velocity, Ground response analysis, Site characterization.

1. Introduction

The frequent earthquakes have caused massive property damages and casualties over the years due to which risk-based seismic microzonation became more important for the governments across the world.There have been several disastrous earthquakes in India in recent years, such as Assam 1897, Kangra 1905, Bihar-Nepal 1934, Assam-Tibet 1950, Uttarkashi 1991 (M=6.5), Latur 1993 (M=6.4), Jabalpur 1997 (M=6.0), Chamoli 1999 (M = 6.8), Bhuj 2001 (M = 7.6) and Kashmir 2005 (M = 7.4). Seismic microzonation consists of mapping seismic hazards related to geology, including subterranean subversive structures, earthquake sources, and site-relevant conditions like seismo-tectonics, seismicity, amplifying seismic motion with "subsurface geology", deep geological factors, groundwater table, soil strata, and geomorphology/topography of land. These maps are used to determine the major risk of ground disturbances and relentless shaking during liquefaction of soil, landslides, and other seismic events. If the sources of earthquakes lie under the sea, a tsunami is also considered. The underlying hazard parameters should be analyzed as per the socioeconomic conditions for an effective and helpful seismic zonation.[1]

According to Anbazhagan et.al [1] the very first attempt was conducted in Yokohama, Japan in the year 1954 where seismic microzonation was done in an urban area, including populated and industrial areas. It included various zones, along with design seismic coefficients and soil conditions for various structures in various zones. Later on, few more earthquake-prone areas were considered for microzonation studies worldwide.Slobet al. [2] has presented a microzonation technique for the Columbian city of Armenia. They employed a 3D layer model in GIS, together with a 1D seismic response using SHAKE, to determine the geographical variation in seismic reaction, which was then compared to Armenia's damage assessment.A lot of studies have been underway since then. Seismic intensity, casualties and building damage due to scenario/target earthquakes were some of the outputs of seismic microzonation initially. Later on, earthquake scenarios started to be developed by the people for possible risks for each area and comprehensive studies were being taken for triggered faults to determine the possibility of earthquake. The seismic conditions and hazards were also investigated in earthquake prone regions. Natural disasters become disasters when affecting social aspects. The level of harm relies on the available infrastructure and density of population. It is vital to know the interrelationships and interactions among complex and diverse entities given the specific magnitude of event

Even while large earthquakes on plate borders are feasible, the possibility of large intraplate earthquakes is also a major issue. Figure.1 depicts the distribution of earthquakes across the Indian subcontinent, as well as the locations of cities, based on a seismic microzonation research

As the first step to studying earthquake risk, it includes contributions from seismology, geology, geotechnical, geophysics, and structural engineering fields. Geological and tectonic formations in the field of study are essential to understanding seismic sources and creating realistic earthquake hazard models. To determine the seismic hazard, seismic microzonation involves a thorough field survey. They also evaluate risks in the area. Microzonation is based on modelling the rupture mechanism at an earthquake's source, analyzing wave propagation through the ground surface to the top of bed rock, determining the effect of the local soil profile, and developing a hazard map indicating the area's vulnerability to potential seismic hazard. Tunnels, water and sewage lines, gas and oil lines, and electricity and communication networks will all benefit from seismic microzonation.

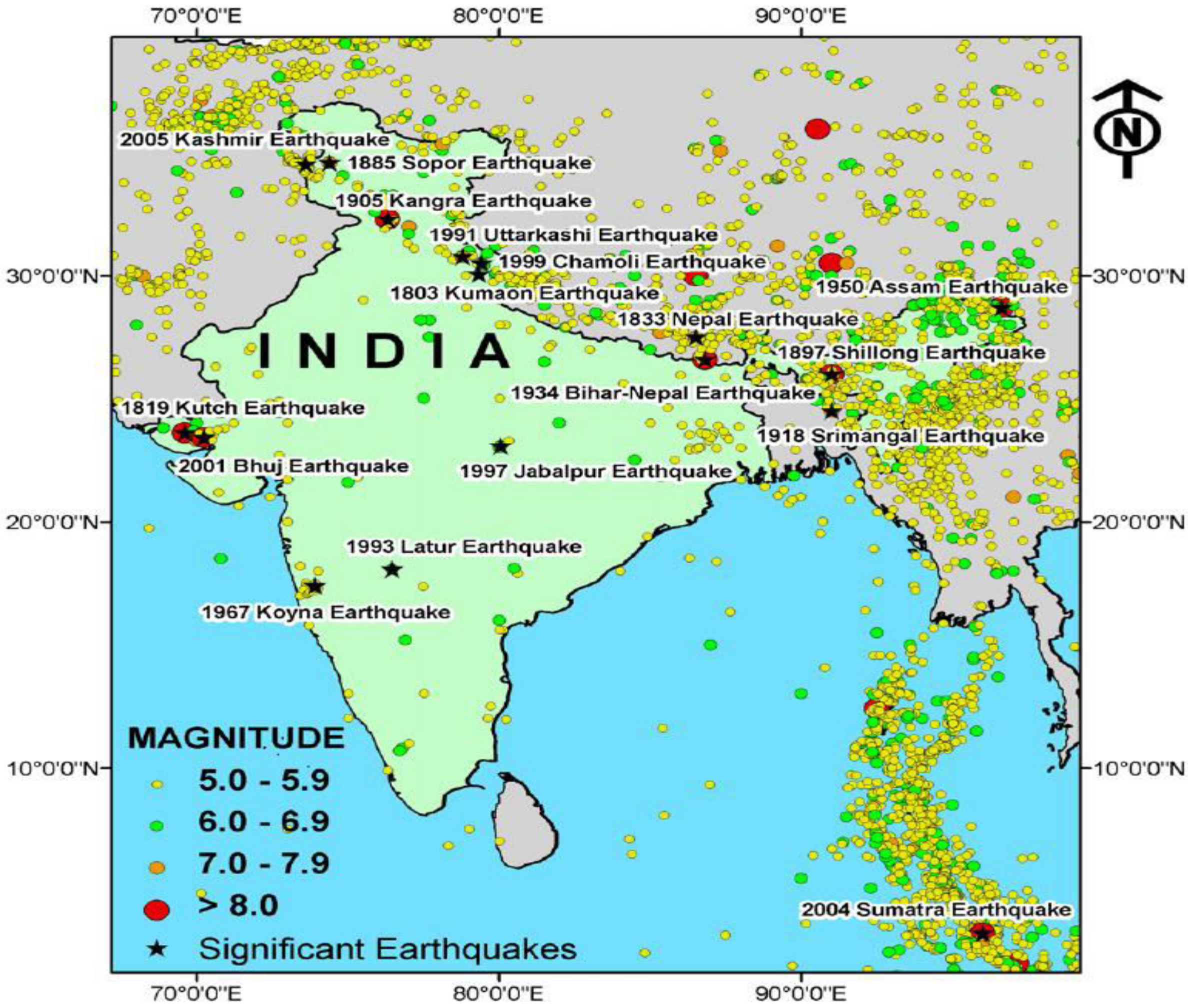

Figure 1: Earthquakes in India with microzonation cities (modified after Walling and Mohanty, [3])

2. Principles of Seismic Microzonation and Zoning

In seismic microzonation, a region is divided into different zones based on the level of seismic hazards. As a result, earthquake hazard can be identified, and engineering design and land-use planning for subsequent urban development will be facilitated. The definition of unsuitable areas, the selection of ideal building heights and types, the retrofitting of critical buildings, as well as providing earthquake guidance to the general population, earthquake insurance, and emergency response plans will be crucial.Seismic zoning involves division of a national boundary into various seismic zones to indicate the levels of peak ground acceleration or seismic intensity expected for various return periods on the basis of predicted and historic intensity of ground motion.As shown in figure 2, the Bureau of Indian Standards [4] has classified the country into several seismic zones (Zone II to Zone V) with different peak ground accelerations (0.16 g to > 0.36 g) with a 10% increase in PGA over the next 50 years. The northeast of India falls in zone V of the seismic hazard zonation map of India, the area with the highest vulnerability.

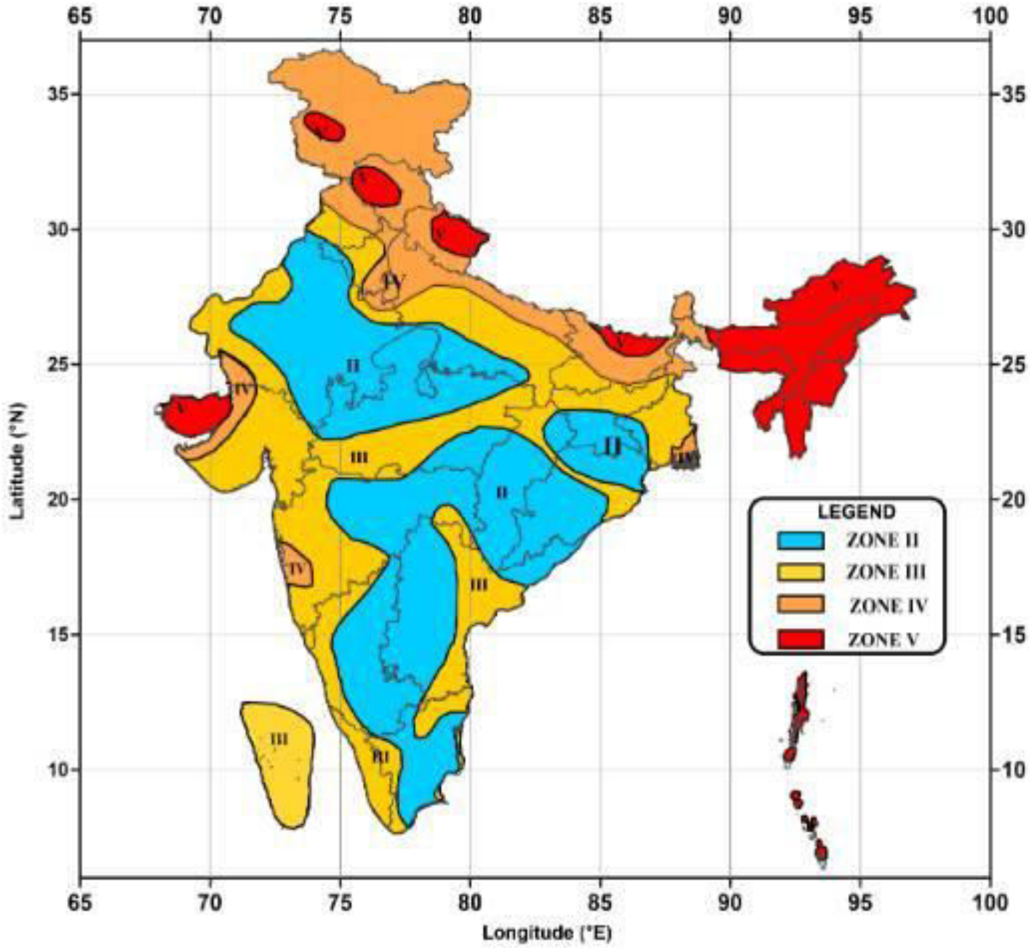

Figure.2 Seismic Zonation Map of India (BIS, 2002) with an inset showing the area occupied by different seismic hazard zones.

For seismic microzonation of an area, several inputs such as seismicity, geology, and geotechnical characteristics are required. The microzonation will be rated according to the scope of the investigation and the specifics of the research. According to the technical committee on earthquake geotechnical engineering (TC4) of the International society of soil mechanics and geotechnical engineering[5] the three grades of approach are described as below with reference to Table. 1, a Level Imap can be prepared with a scale of 1:1,000,000 – 1:50,000, and the ground motion can be calculated using historical earthquakes and existing geological and geomorphological maps. Level II maps are those with a scale of 1:100,000-1:10,000 and ground motion assessments based on microtremor and simplified geotechnical studies. Based on full geotechnical studies and ground motion analysis, the Level III map elaborates ground motion analyzed at a scale of 1:25,000-1:5,000. The scale of zonation is determined by the database available and the desired quality of the zonation map.

Table.1 (TC4-ISSMGE 1999) the three grades of approach are described as below:

	Level I	Level II	Level III
Ground motion	**Historical earthquakes, Geological map, existing information, Previous research reports.**	**Microtremor, Simplified Geotechnical study.**	**Geotechnical Investigation, Ground response analysis.**
Scale of mapping	**1:1,000,000 – 1:50,000**	**1:100,000-1:10,000**	**1:25,000-1:5,000**

3. **Methodology**

In the first phase, seismotectonic map is needed to characterize the earthquake source in the study area more accurately. On a GIS platform, the seismicity of the site is depicted with magnitudes based on an earthquake catalogue. Seismotectonic units, faults, and lineaments that are seismically active are identified and characterized. The parameters at rock level can be mapped using both deterministic and probabilistic analysis. As part of the second phase, geological, geomorphological, geophysical and geotechnical data will be used to characterize the site in more detail. It is remarkable how local geology can modify ground motions transferred from a distant earthquake and cause local soil failures such as liquefaction. Subsoil properties are the most important information that can be used to determine whether a site is susceptible to earthquakes. Following the second phase, the third phase involves data analysis and interpretation of the accumulated data. This can be used to estimate site-specific effects, such as landslides, liquefaction, and amplification. In order to assess the site-specific ground level hazard parameter, the SHAKE2000 software will be used.
After that, the seismic zonation map can be prepared according to the required seismic hazard parameters using the accepted scales. The final macro or micro zonation map of a region is created by combining all of the above maps using Analytic Hierarchy Process by assigning weights and ranks based on each hazard parameter's importance. The final map of the region can be used to determine high-risk areas where seismic risk and vulnerability assessments are required. All of these maps are created using a GIS platform that incorporates all spatial parameters in the city/urban center, allowing them to be utilized for hazard detection, town planning, construction and retrofitting and disaster risk management.Figure 3 shows the flow chart of the implementation methodology for seismic microzonation.

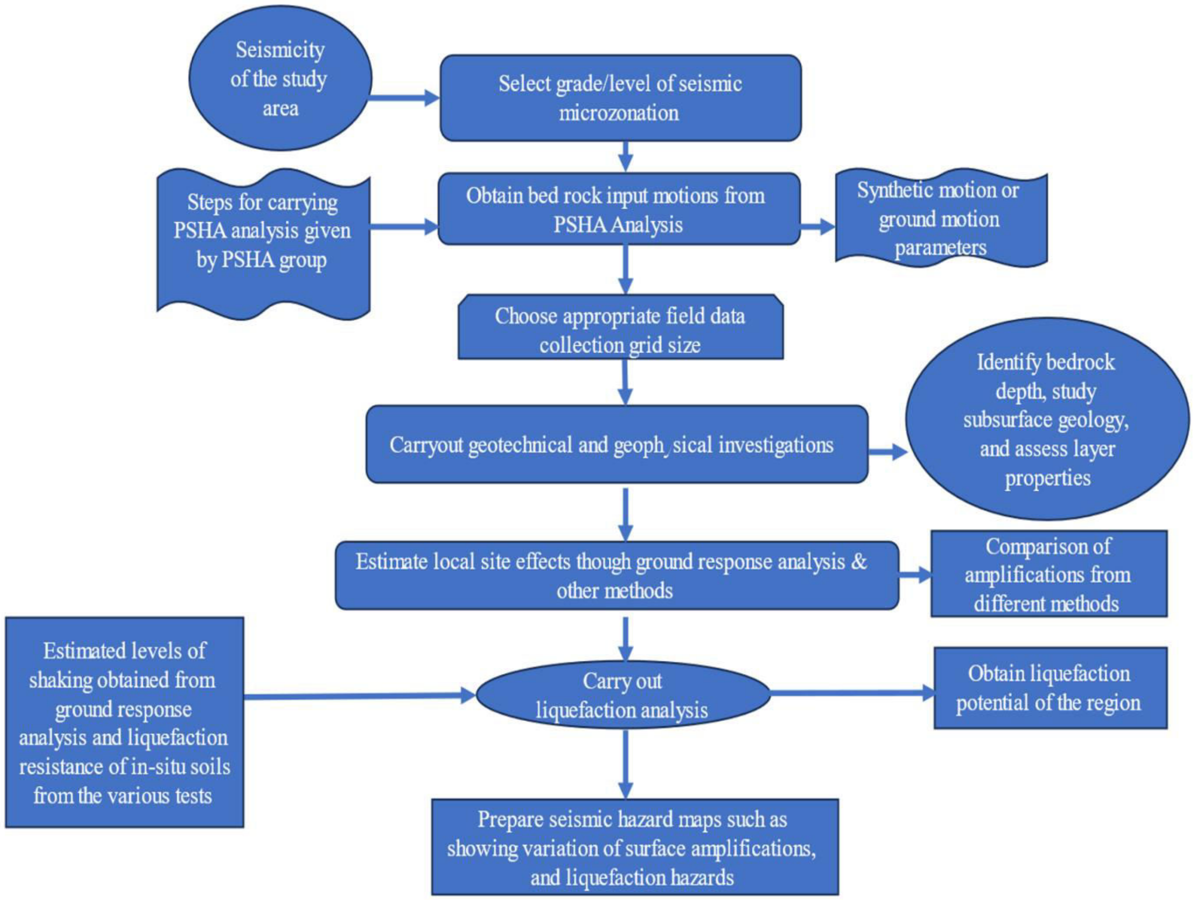

Figure 3. flow chart of the implementation methodology for seismic microzonation.

4. Brief Summary of Seismic Microzonation carried out so far across the globe:Seismic Microzonation in Metropolitan Vancouver, Canada

A seismic microzonation multi-year project is being done for mapping local changes in site response across Metro Vancouver, Canada. Molnar et al. [6] presented their progress in hazard mapping of site amplification in Metropolitan Vancouver, British Columbia after their first field study. They conducted one-dimensional microzonation with relevant geophysical, geological, and geotechnical datasets from private and online sources to develop a local 3D geo-database. Site characterization is performed around 20 strong-motion stations based on stiff and soft sediments with several in-situ non-invasive seismic approaches, such as "micro-tremor and surface-wave range horizontal-to-vertical spectral ratio (MHVSR)" to record depth profiles of "shear wave velocity (Vs)". They also compiled all the earthquake recordings collected from six events with around 3.9 magnitudes to determine site amplification.

The most prevalent site effect earthquake phenomenon is the effect of near-surface geology in the amplitude of topmost 100s of meters and earthquake shaking duration [7]. The time-averaged Vs30 or "Vs of upper 30 meters" has been used as a common indicator or metric for earthquake site response since the 1990s [8], which is still common in analyzing seismic hazards. Vs30 can capture the amplification which is based on broadband impedance and correlate the same with earthquake motions which are observed but don't cause amplification at specific ranges because of one-dimensional resonance in soil column and 3D topography or basin effects [9-11]

Seismic Microzonation in Yanbu city, Western Saudi Arabia

Yanbu City is located in the active tectonic setting of the Red Sea and affected by geodynamic effects in the Red Sea. The structures either transform faults running parallel to or throughout the Red Sea. Some faults extend around thousands of kilometers within [12-13]. Across these faults, the relative movements lead to threatening and strong earthquakes. Historical details [14-16] and recent studies [17-19] on Yanbu city have found some major earthquake activities which should be considered for right future plans.

Microtremor measurements are the most widely-used tool across the world to estimate site response in urban regions [20]. This tool has been deployed in around 85 sites across Yanbu city to determine ground shaking effects and seismic microzonation. The "horizontal to vertical (H/V)" spectral analysis was conducted in all sites for estimating the amplification and resonance frequency for ground-level vibration. There is a clear peak in the H/V curve displayed in the H/V curve for amplitude which suggests soil-bedrock contrast. However, other areas present over a peak which have several impedance contrasts across the sedimentary cover. The analyses have clearly presented that both parameters significantly vary across the city, especially because of lateral changes in soil type and/or soil thickness in the city. The basin geometry had 2D and 3D effects on the result.

Seismic Microzonation in Myanmar's Mandalay City

Mandalay City of Myanmar is a well-known cultural hub with the population of over 1 million. It is located at the center of Myanmar and shares its boundary with Moemeik and Shweli faults towards the north, Sagaing fault around 8 km west, and Kyaukkyan fault and Shan Scrap fault towards the east. The major right-lateral strike-slip continental fault is Sagaing, i.e. stretched over 1200 km. It is connected to the spreading center of Andaman at southern termination and it was noticed earlier and also confirmed by many researchers [21-28].

It is very important to understand "Peak Ground Acceleration (PGA)" parameters for environmental planning and controlling seismic hazard in Mandalay City. Thein et al [29] collected 50 measurements with "Standard Penetration Tests (SPT)" in Mandalay City to calculate Vs30 or average shear velocity for seismic microzonation. The top layer has been found with "$Vs30 \leq 220$ m/s". Linear magnification and predominant periods were used to estimate ground motion characteristics with varied reflection analyses.

Seismic Microzonation in Ottawa and Montreal, Canada

Montreal and Ottawa are just behind Vancouver in second and third positions respectively in terms of seismic hazard and population density. Majority of parts of both cities are covered by low sheer and soft velocity and postglacial sediments which overlap glacial bedrock or high shear till causing very high seismic impedance at thin depths. To provide robust and reliable velocity-depth shear wave profiles in the areas of study, a lot of methods like "multi-channel analysis of surface waves (MASW), seismic reflection/refraction, borehole measurements," horizontal-to-vertical spectral ratios (HVSR)" of ambient noise, and seismic shear wave high resolution reflection are applicable. Reflected and refracted shear waves and surface waves are enabled in firm bedrock and sediments with high impedance causing shear wave profiles of velocity-depth for classification of soil site.

Basic resonance frequencies are used for amplification of soil sites locally in Montreal along with amplitudes from HVSR microtremor approaches. Shear wave velocity estimates have been gathered from the ground level to Vs30 or 30m of depth with shear wave surface reflection/refraction analysis. High-quality land-streamer/Minivib wave reflection profiling, MASW and shear wave downhole measurements are conducted in both cities to attain velocity-depth, shear wave functions to have correlations with other approaches. Both cities have developed a vast borehole database of bedrock and unconsolidated overburden materials serving as framework to develop regional hazard models [30].

Seismic Hazard Study of Ethiopia

Faults release energy suddenly and cause earthquakes. Earthquakes and other natural calamities can neither be prevented or predicted. It is possible to minimize the severity of damages by developing the right infrastructure, including microzonation studies, earthquake-resistant structures, and the right construction procedures. The effect of earthquake damages relies on the path, source, and site conditions. Groundwater, surface hydrology, and topography (hill, slope, valley, basin and ridge effects) affect the ground motion. Structural damage, lifeline hazards, and structure failures are ground shaking and cause seismic damages. The Ethiopian rift system controls the medium-to-large, i.e. <6, magnitude of earthquake in Ethiopia. The temporal and spatial changes of ground motions of earthquake must be addressed with different methodologies discussed by **Ayele et al. [31].** The "deterministic seismic hazard assessment (DSHA)", "probabilistic seismic hazard assessment (PSHA)" and "dynamic site response analysis" are the general methodologies to analyze ground motions and earthquake damage. Ethiopia is going through a significant infrastructural growth, such as industrial parks, railways, and roads, agricultural activities, and rising population throughout the Ethiopian Rift. Special attention must be given to ground failures by earthquakes to mitigate damages from earthquakes.

5 Seismic Microzonation of Major Cities in India

The vulnerability and earthquake risk is quite evident in India as around 59% of land is vulnerable to medium to extreme earthquakes. Particularly North India and Himalayan belt have faced a lot of moderate and strong earthquakes since the 18th century. There is a record of having major earthquakes with over 7.0 MW (magnitude). Rao and Rathod [32] focused on progressive changes on "seismic zonation map" of the country officially done by national agencies, International Program, and individual studies. They summarize the work of seismic microzonation performed for some major Indian megacities. They also analyzed zonation maps and methods which have been adopted. They presented a case study of microzonation in Delhi NCR while focusing on improvements for better utilization of such techniques in future.

Microzonation has been widely recognized as the most prevalent tool for risk evaluation and seismic hazard evaluation considering the site and source conditions in ground motion. It refers to the process of evaluating and mapping common hazards in an urban area which could be from shaking of the ground during an earthquake [33]. These hazards consist of liquefaction, ground motion amplification, as well as landslides. There are two aspects of safety from earthquake risks – (1) structural safety from hazardous dynamic force and (2) site safety as per geotechnical phenomena [34]. Several studies have been conducted worldwide to quantify the earthquake risk due to seismic activities in different areas. A historical analysis can be helpful considering earlier events for preparing seismic hazard profiles in a region, especially related to seismic activity [35-37] and seismic vulnerability globally [38-39].

Seismic microzonation of urban Jabalpur

Seismic Microzonation of Jabalpur Urban Area [40]was the first study in India on microzonation of Indian cities as an experiment and example. India's Indian Metrology Department, New Delhi, the Central Region Geological Survey Government Engineering College, Jabalpur, Nagpur, National Geophysical Research Institute (NGRI) Hyderabad and Central Building Research Institute (CBRI), Roorkeeconducted this activity as nodal national agencies. Based on Joyner and Boore's attenuation relation [41], seismic hazard analysis was done deterministically. Geological, geotechnical, and geophysical studies were used to characterize the ground. Based on these findings, a first-level microzonation map was created. Ground amplification at local sites in the frequency range of 0.1 - 10 Hz was obtained at more than 100 sites in and around Jabalpur using the conventional Nakamura technique to estimate the predominant frequencies and the site amplification at those frequencies for each site. Sites in Jabalpur were classified using geophysical methods of multichannel analysis of surface waves (1997), the National Earthquake Hazard Research Program (NEHRP,1998), and the standard building code. In order to calculate predominant frequency maps, Nakamura type studies and receiver function studies were used. This report includes vulnerability and risk analyses as well as preliminary seismic risk maps and microzonation at the second level.

Seismic Microzonation in Kolkata

According to Nandy [42] damage intensities and ground shaking from seismic activities are based on source, magnitude, and path of energy and conditions of areas. Effects of geology on shaking of grounds have long been considered for evaluating earthquake risks. It is possible to decipher site response parameters from geological setting, geotechnical soil properties, and instrumental studies that can help estimate risk factors by getting away from deep path effects and removing the source as these effects are similar on the surface of soil and bedrock records. Local amplification has been shown to be responsible over unconsolidated sediments in San Francisco for variation of intensity above 2 degrees during the recent Loma Prieta event and 1906 earthquake. There are various examples worldwide, such as the effects of the Gujarat earthquake in 2001. For fastest growing areas of Kolkata and built areas, seismic microzonation of areas in seismic zone level 4 and 5 is important to retrofit vulnerable and old complexes and to have seismic coefficient to new installations and constructions.

Seismicity and Seismic Hazard in Delhi

Parvez et al. [43] calculated seismic ground motion in Delhi City using a hybrid approach relying on modal summation and finite-difference modelling. In this study, response spectra were calculated from signals generated along the laterally changing portion and compared to equivalent signals synthesized for the bedrock references regional model. It has been demonstrated that sedimentary cover increases signal amplitude (greater amplification), especially in the transverse and radial components, when the source position is reversed to the opposite side of the cross section. At high frequencies (over 4 Hz), the vertical component is amplified significantly more than at lower frequencies.The first-order seismic microzonation map of Delhi was created by Mohanty et al. [44], using five thematic layers: PGA contours, soil types at 6 m depth, geology, groundwater fluctuations, and bedrock depth. Thematic maps were weighted on a 5-1 scale based on their contribution to seismic hazards during the integration process. The following subjects are weighted: PGA (0.333), geology (0.20), soil (0.26), groundwater (0.133), and bedrock depth (0.066). Using GIS, thematic vector layers were overlapping and combined.Kolathayar[45] reviews recent and historic seismicity in Delhi and presents hazard maps with ward-wise population information. There are several factors that make earthquakes more destructive. Construction quality of buildings and population density in an area are two such factors that highly affect the risk during earthquake hazards. The author analyzes seismic hazards in Delhi with latest info on seismic sources and earthquakes in the radius of 300 km in the city with world-class approach. This study considers ten attenuation relationships for active tectonic areas. They were ranked with a log-likelihood approach. Apart from the given population maps, ward-wise population maps were introduced on the basis of 2011 census data. It presents a population map and hazard contour map to review the seismic risk. It is an attempt to overlay the risk with population maps and distribution of several categories of population reflecting the exposure of seismic risk to various areas of Delhi.

Seismic Microzonation of Dehradun city

Based on Mahajan et al [46], seismic microzonation was developed in Dehradun, which lies near the northwest Himalayan foothills. In soil response modelling, shear wave velocity (Vs), a critical soil parameter, was assessed using seismic profiling based on multichannel analysis of surface waves. A total of fifty sites were explored throughout the city using survey lines ranging between 72 and 96 metres long. Many 1-D and interpolated 2-D profiles have been created up to a depth of 30–40 m. In the SHAKE2000 software, the Vs were combined with seismic input motion from the recent Chamoli earthquake. The estimated Vs are greater in the northern half of the research area (i.e., 200–700 m/s from the surface to a depth of about 30 m) as compared to the south and southwest sections of the city (180–400 m/s). At 3–4, 2–2.5, and 1–1.5 Hz, peak amplification is also observed in the northern, central, and south-southwestern regions of the city. Dehradun's seismic microzonation can be improved by analyzing the spatial distributions of shear wave velocity and spectral accelerations..

Seismic Microzonation of Bangalore Region

Anbazhagan et al. [47] published a study on seismic hazard analysis, which included local site effects and microzonation of Bangalore. Bangalore's ground motion is predicted to be 0.15g at rock level, according to the study. Multichannel surface wave analysis (MASW) as well as traditional penetration testing are used to assess soil characterisation. There has been a correlation established between the measured shear wave velocity and SPT "N" values. In a theoretical ground response study using SPT and MASW data, SHAKE2000 software was used for analysis; the results were comparable. The relationship between low strain shear modulus and SPT "N" values has been also established. A microtremor experiment was also used to study site reaction. The studies above indicate that Bangalore's predominant period ranges from 3Hz to 12Hz. The liquefaction risk of Bangalore is also calculated, and the results show that Bangalore is not at risk of liquefaction.

5 Critical summary and Conclusion

Seismic microzonation has come out to be an effective technology to control seismic hazards with the given land use management. Microzonation is just one aspect to mitigate earthquake risks. Construction and structure codes are other factors to be considered. Seismic microzonation maps don't show hazard parameters in detail at a particular building. Rather, they guide on specific site testing. The seismic zonation maps are majorly at national levels and seismic microzonation needs studies at a large scale for a city. There is a lack of support about changes in map scales to estimate site characterization and earthquake risks. Hence, seismic microzonation is mainly aimed to provide structural design details by taking the place of maps for national microzonation. However, it is uncertain to use this approach as there is still a lack of uniformity and reliability in such studies.There have been many devastating earthquakes in India in recent years. It is impossible to predict earthquakes or prevent them. Proper land use planning and safe construction practices can minimize the severity of the damages. For effective mitigation of seismic hazards, seismic microzonation provides the necessary information. The severity of earthquake shaking damages is largely determined by local site effects, as discussed in the current report. A site's hydrogeological conditions, topography, and geotechnical characteristics can significantly affect bed rock motions. In addition to the geotechnical characteristics of the local soils, earthquake associated disasters such as liquefaction, lateral spreading, sand boiling, and landslides are also dependent on them. It is therefore critical to conduct proper geotechnical/geophysical investigations as part of seismic microzonation studies.In this study, detailed information is provided on the existing methodologies and procedures for seismic microzonation, and guidelines will be provided for conducting appropriate tests and methodology to standardize the seismic microzonation process.Interdisciplinary interpretation is still needed to overcome this issue. Seismic microzonation needs data from engineering and civil engineering geology, especially for geotechnical analysis, while seismic microzonation doesn't demand such input. Seismic microzonation should also be included in municipal, regional, and international administrations for seismic codes, urban planning, and civil protection. Several countries have produced guidelines for seismicmicrozonation.

Conflict of interest: The authors declare that they have no conflict of interest.

Author Contributions: AKA: Conceptualization, Formal analysis, writing – Original preparation; JT: Revision and editing of drafted manuscript; supervision.

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