

43 refinement through multidisciplinary approaches and region-specific investigations is necessary to
44 transform these maps into effective tools for civil engineers and policymakers.

45 **Authors keywords:** Seismic Hazard Assessment; Probabilistic seismic hazard analysis (PSHA);
46 Seismic site characterization; Ground response analysis (GRA).

47 **Introduction**

48 Over the historic times, earthquakes have always culminated to be a devastating hazard. Numerous
49 significant earthquakes have struck various regions worldwide, including Armenia (1988, M_s 6.8),
50 Iran (1990, M_w 7.4), the United States (1994, M_w 6.7), Japan (1995, M_w 6.9), Mexico (1985, M_w
51 8.0), Taiwan (1999, M_w 7.7), India (2001, M_w 7.7), Alaska (2002, M_w 7.9), Sumatra (2004, M_w
52 5.6), Pakistan (2005, M_w 7.6), China (2008, M_w 7.9), Haiti (2010, M_w 7.0), Japan (2011, M_w 9.0-
53 9.1), Chile (2015, M_w 8.3–8.4), Turkey (2023, M_w 7.8), Tonga Islands (2025, M_w 7.0), Tibet (2025,
54 M_w 7.1) and Myanmar (2025, M_w 7.7). These devastating occurrences have driven extensive
55 research into seismic hazards, focusing on subsurface engineering attributes, regional tectonic
56 features, and geological formations as fundamental elements. Consequently, global efforts, such
57 as the Global Seismic Hazard Assessment Program (GSHAP), have facilitated seismic risk
58 evaluations across multiple regions (Giardini et al. 1999). The Indian subcontinent ranks among
59 the most seismically active regions in the world due to its complex tectonic framework. The
60 primary seismogenic zones are linked to the convergent plate boundary where the Indian Plate
61 collides with the Eurasian Plate. This tectonic activity is prominently manifested in the Kirthar-
62 Sulaiman ranges, the Himalayan Mountain belt, and the Arakan-Yoma fold and thrust zone, which
63 delineate the northern and northeastern boundaries of the subcontinent (Parvez et al. 2003). These
64 regions are characterized by frequent earthquakes, varying from moderate to large magnitudes,
65 and are critical for understanding seismic hazard in South Asia. India has a history of experiencing

66 major earthquakes, including Assam (1897, M_w 8.7), Kangra (1905, M_w 8.6), Bihar-Nepal (1934,
67 M_w 8.4), and Assam-Tibet (1950, M_w 8.7). More recently, the nation has endured significant
68 seismic events in Uttarkashi (1991, M_w 6.5), Latur (1993, M_w 6.4), Jabalpur (1997, M_w 6.0),
69 Chamoli (1999, M_w 6.8), Bhuj (2001, M_w 7.7), Kashmir (2005, M_w 7.4), 2011 Sikkim earthquake
70 (M_w 6.9), 2016 Manipur Earthquake (M_w 6.7), 2017 Tripura earthquake (M_w 5.7), 2020 Mizoram
71 earthquake (M_w 5.6), 2021 Assam earthquake (M_w 6.4), 2022 Arunachal Pradesh earthquake (M_w
72 5.7), 2023 Meghalaya (M_w 5.4), 2025 Manipur earthquake (M_w 5.7). According to data from
73 NDMA in 2010, around 60% of the Indian land is in risk from earthquakes. Earthquakes can
74 happen anytime and can bring major threats like site deformation, ground displacement,
75 liquefaction, landslides and tsunamis. The consequences of floods worsen when buildings are put
76 together quickly, cities are overcrowded and city planning isn't effective. Additionally, these strain
77 gaps raise the chances of significant earthquakes in subduction zones. Because there are many
78 minor tremors there, scientists see a risk of a large earthquake occurring in the central Himalayan
79 seismic strain gap. Because of new technology in earthquake-resistant design, improvements in
80 how structures are built are still required to prevent large losses and damage. As more people move
81 to areas near faults, it is now more important than ever to do seismic microzonation and assess
82 natural hazards.

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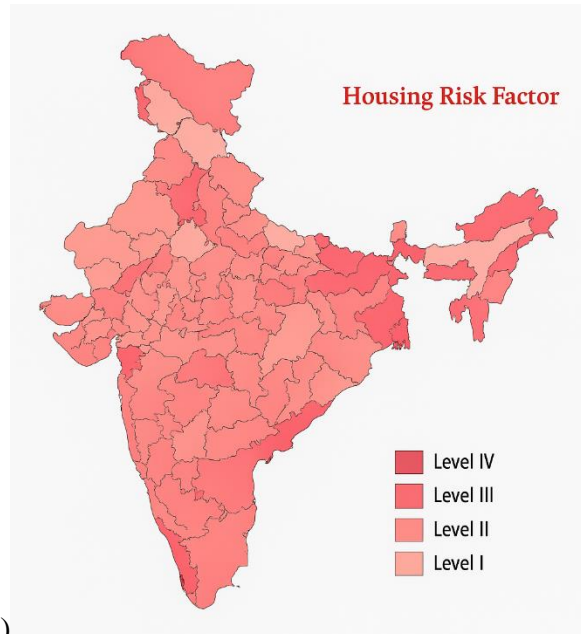
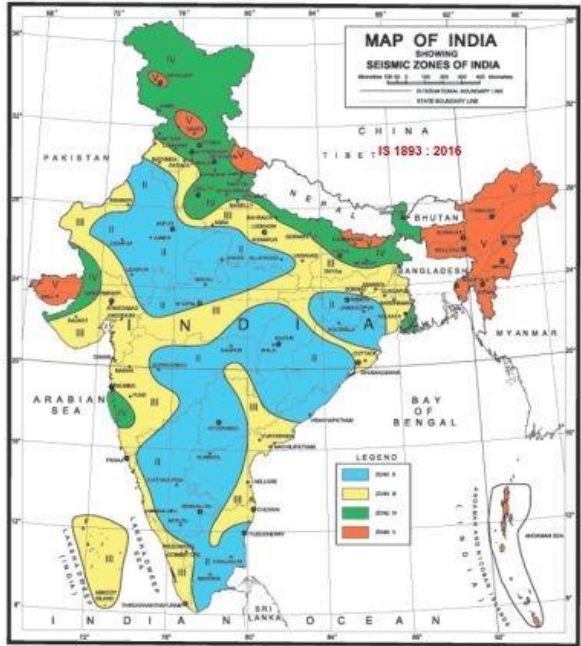
84 Seismic microzonation entails dividing a region into smaller zones based on localized earthquake
85 effects to aid in new construction planning and the retrofitting of existing buildings. This process
86 assesses soil behavior under seismic activity and evaluates earthquake hazards on a finer scale by
87 mapping and computing impacts. Microzonation maps, which consider local site conditions, are
88 valuable tools for urban development and designing earthquake-resistant infrastructure. Various

89 Indian cities have been analyzed for seismic hazards, including Delhi (Rao and Satyam 2004),
90 Bangalore (Anbazhagan and Sitharam 2008), Imphal (Raghu Kanth and Nadh Somala 2009),
91 Kolkata (Govindaraju and Bhattacharya 2012), Ahmedabad (Rao et al. 2012), Gujarat (Shukla and
92 Choudhury 2012b), Kanpur (Jishnu et al. 2013, Anbazhagan et al. 2017a), Haryana (Puri and Jain
93 2019), Mumbai (Desai and Choudhury, 2015), Vijayawada (Satyam and Towhata 2016), Surat
94 (Singh et al. 2017), Chennai (Nampally et al. 2018) and Vishakhapatnam (Putti and Satyam, 2018).
95 These studies highlight the significance of site-specific ground motion estimation in ensuring
96 structural safety against earthquakes.

97
98 In seismic microzonation, techniques used include probabilistic and deterministic seismic hazard
99 evaluations, site description, ground wave analysis and monitoring liquefaction risks. PSHA helps
100 estimate earthquake hazards by looking at the possible sources of earthquakes, how often they
101 occur and the chance that ground motion levels will reach particular limits. DSHA, differently,
102 evaluates seismic hazards by using the most reasonable maximum earthquake scenario for a fault.
103 The use of both approaches increases our knowledge about seismic risks and is done when needed.
104 Mihalic et al. (2011) describe in detail the concepts and approaches used in seismic microzonation
105 for the purposes of hazard assessment and urban planning. Although the paper mainly explores
106 PGA and Sa, it fails to discuss unconventional strategies that mix PSHA with microzonation results
107 at specific locations. Another limitation is the lack of case studies from regions with heterogeneous
108 subsurface conditions, which could illustrate how microzonation practices adapt to varying
109 geological and geotechnical complexities. Site characterization involves geological, geophysical,
110 and geotechnical studies, utilizing parameters like average seismic shear-wave velocity from the
111 surface to a depth of 30 meters (V_{s30}), Standard Penetration Test (SPT) values and subsurface

112 stratigraphy, to categorize sites according to their seismic response. These studies examine how
113 different layers in the ground respond to seismic vibrations which allows engineers to determine
114 PGA and response spectra needed for the design and protection of buildings against earthquakes.

115
116 Walling and Mohanty (2009) described the progress made in India from early general seismic
117 zoning to more specific microzonation for urban areas. It called for merging geophysical,
118 geological and geotechnical information to look at seismic hazards, including PGA and factors
119 that amplify ground shaking at certain sites. Unfortunately, the text did not look closely at hurdles
120 in getting data and applying microzonation rules in less developed parts of the world. Besides, the
121 manuscript did not focus on newer approaches such as PSHA or advanced computer models, so it
122 does not meet the needs of modern urban planning. This shows that more improvements are needed
123 in microzonation techniques to protect against hazards. In 1962 (IS 1893, 1962), the Bureau of
124 Indian Standards (BIS) made available the initial version of the Earthquake Hazard Zonation Map
125 of India. Since then, it has been periodically updated based on significant earthquakes that have
126 occurred in the country. The most recent version was published in 2016 (IS 1893 Part 1, 2016).
127 According to this map, approximately 56% of India's geographical area is susceptible to moderate
128 to severe earthquake shaking, as shown in Fig. 1a. A housing risk factor is used to understand the
129 overall status of housing in India (Ramancharla and Murty, 2014). This factor is obtained by
130 multiplying seismic zone factor by number of houses per km² for each district in India in each
131 corresponding seismic zone (Fig. 1b). Figure 2 illustrates worldwide disaster-related deaths from
132 earthquakes and other disasters between 2000 and 2024, based on data from Emergency Events
133 Database (EM-DAT; <https://public.emdat.be/>).



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(a)

(b)

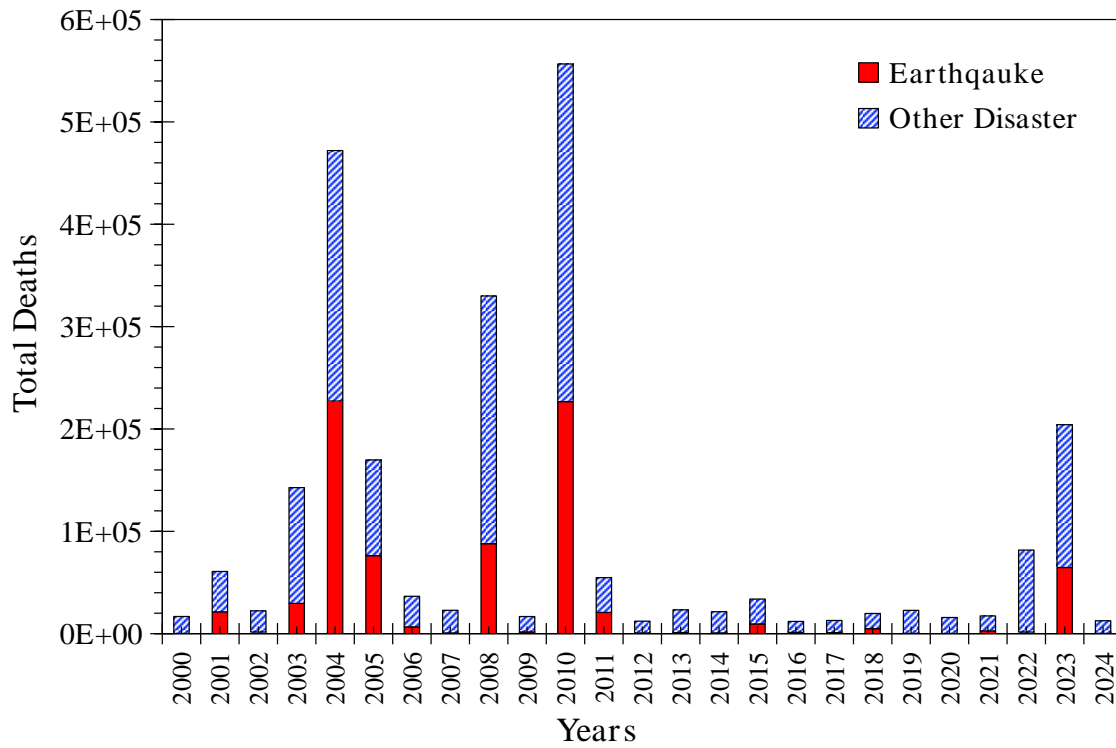
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Fig. 1. (a) Seismic Hazard Map (IS 1893 Part 1, 2016), (b) Housing Threat Factor (after

136

Ramancharla and Murty 2014).

137



138

139 **Fig. 2.** Worldwide Disaster related deaths (2000–2024) based on EM-DAT data.

140 (www.emdat.be)

141 The continuous subduction of Indian plate beneath the Eurasian plate has driven the formation of
142 the Himalayas (Oldham 1883, 1899; Kayal 1987; Kumar et al. 2005; Mukhopadhyay 1992;
143 Mukhopadhyay and Dasgupta 1988; Nandy 2001; Tandon and Srivastava 1975; Mitra et al. 2005)
144 and has consequently led to the development of seismotectonic zone all along the Himalayan belt.
145 Northeast India ranks among the most seismically active plate tectonic regions globally (Kayal
146 1998; Tewari 2000). Numerous high-magnitude earthquakes have struck this region, where
147 frequent foreshocks and aftershocks indicate persistent seismic activity. Due to this high
148 seismicity, government regulations limit high-rise construction, impacting regional development.
149 Studies have been conducted for seismic hazard assessment in north-east Indian cities like
150 Guwahati (Raghu Kanth 2010, Nath et al. 2008, 2009), Sikkim (Nath et al. 2005, 2008), Manipur
151 (Pallav et al. 2010), Tripura and Mizoram (Sitharam and Sil 2014).

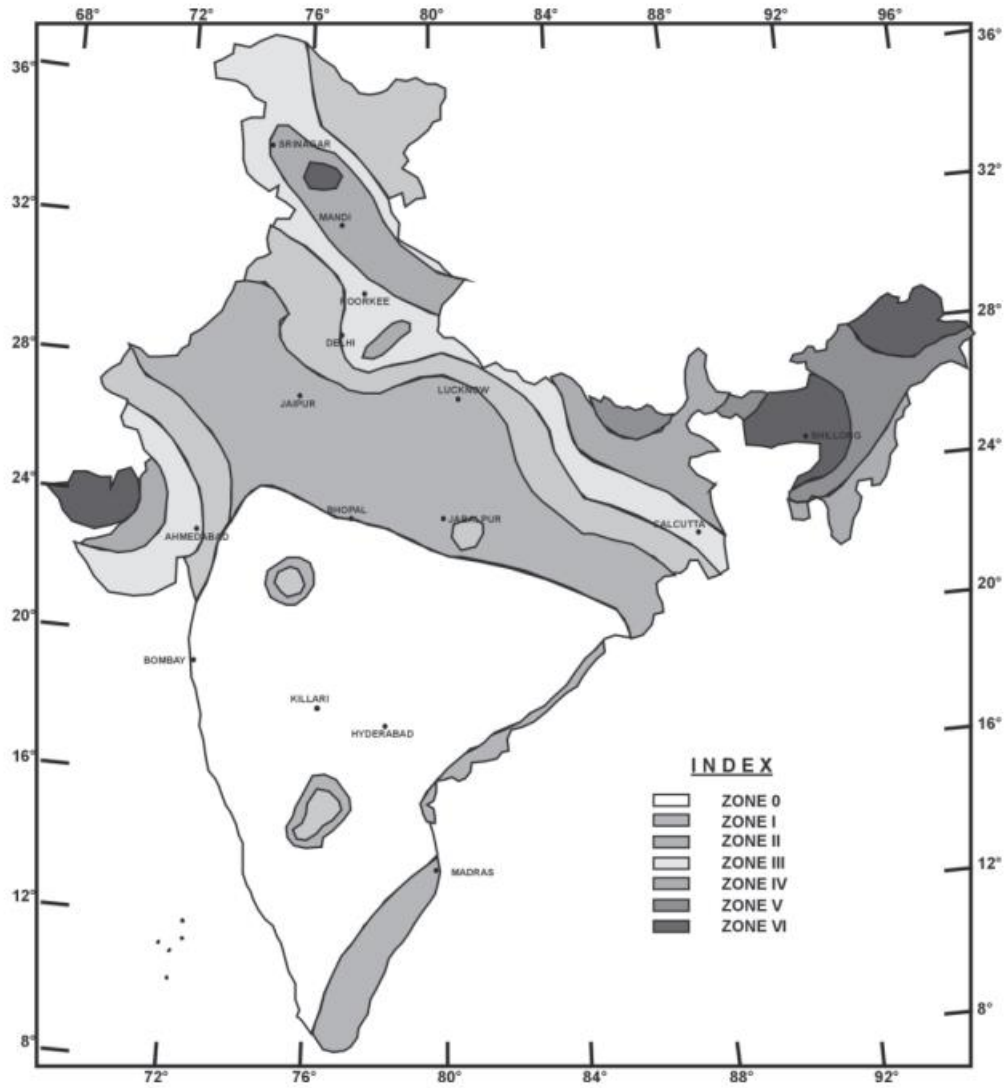
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153 Despite extensive research in various Indian cities, a comprehensive seismic hazard assessment
154 for Itanagar is yet to be conducted, even though the region is highly prone to seismic shaking and
155 ground amplification. The increasing population, along with rapid and unregulated urbanization,
156 further exacerbates the risk. Itanagar, the capital of Arunachal Pradesh, covers approximately 200
157 km² and is located in the outer Himalayas. The area has rough topography, where elevations are
158 between 80 m and 1540 m and is covered in Quaternary fluvial deposits, resulting in river
159 terraces and valley fills. Past earthquakes have been detected in the Siwalik and Quaternary
160 sediments which clearly shows why microzonation is important. Because Itanagar lies in Zone V
161 of the highest seismic risk which has a zone factor of 0.36g according to IS 1893 Part 1 (2016), it

162 is highly susceptible to earthquakes. Doing a comprehensive study of seismic microzonation
163 allows you to assess the ground in an area, determine seismic dangers and put earthquake
164 protection measures in place. The review highlights the importance of carrying out a proper
165 seismic hazard study in Itanagar. If this study is done thoroughly, local planners, engineers and
166 policy experts can build infrastructure that is safe from the impact of earthquakes. By examining
167 how seismic codes and zonation maps have evolved over time, we can understand better how the
168 standards for earthquake-resistance have been adjusted after large earthquakes.

169 **Seismic zonation maps of India: Evolution and revisions**

170 Following the disaster caused by the 1934 Bihar-Nepal earthquake, the Geological Survey of India
171 (GSI) produced India's first seismic hazard map in 1935. Then, in 1947, the Indian Standards
172 Institution (ISI) was created to create standards for industrial and commercial products. The bureau
173 was renamed the Bureau of Indian Standards (BIS) in 1986, following the BIS Act and was now
174 given the task of overseeing quality of products, developing standards and providing certifications.
175 BIS supports many sectors, including companies, organizations that serve consumers, schools and
176 research groups, agencies in charge of regulation and government offices. As the country's
177 governing agency for seismic hazard evaluation, BIS has a mandate to design and release seismic
178 hazard maps and structural design guidelines, which find general acceptance from other national
179 institutions. In 1962, BIS issued India's first formal seismic zonation map (IS 1893, 1962) based
180 on records of earthquake epicenters and the isoseismal records initially prepared by GSI in 1935.
181 The map took into account earthquakes with magnitudes of 5 or higher, focusing on areas that
182 experienced shaking intensities between V and IX on the Modified Mercalli Intensity (MMI) scale.
183 The country was then categorized into seven seismic zones, ranging from Zone 0 (minimal or no
184 expected damage) to Zone VI (areas of potentially severe damage) as shown in Fig. 3.

185 In the initial seismic zonation, the Deccan Plateau was regarded as relatively stable and assigned
186 Zone 0, indicating minimal seismic hazard. In contrast, a significant portion of northeastern India
187 was classified under Zone VI, representing a high-risk area. A revision of this zonation was
188 undertaken in 1966 (IS 1893, 1966), incorporating additional parameters such as geological
189 characteristics and tectonic structures as shown in Fig. 4. Greater emphasis was placed on tectonic
190 mapping (Tandon 1992), particularly in identifying fault systems, which played a crucial role in
191 redefining the zonal boundaries. The 1962 and 1966 seismic zonation maps separated the Indian
192 subcontinent into seven different zones, each corresponding to an MMI maximum intensity level.
193 These intensity levels were predicted based on either historical seismic data or expected seismicity.
194 The seismic zonation map of India underwent a substantial update in 1970, prompted by the 1967
195 Koyna earthquake, which had a surface wave magnitude of M_s 6.5 and struck the Deccan Plateau
196 then categorized as Zone 0. This unexpected seismic event in a supposedly stable region
197 emphasized the importance of incorporating both geological and geophysical insights into seismic
198 zoning practices. One of the major changes introduced was the removal of Zone 0, as it became
199 scientifically untenable to classify any area as completely devoid of seismic risk. Additionally,
200 Zones V and VI were merged into a single zone under the revised IS 1893 (1970), reducing the
201 total number of seismic zones from seven to five (Fig. 5).

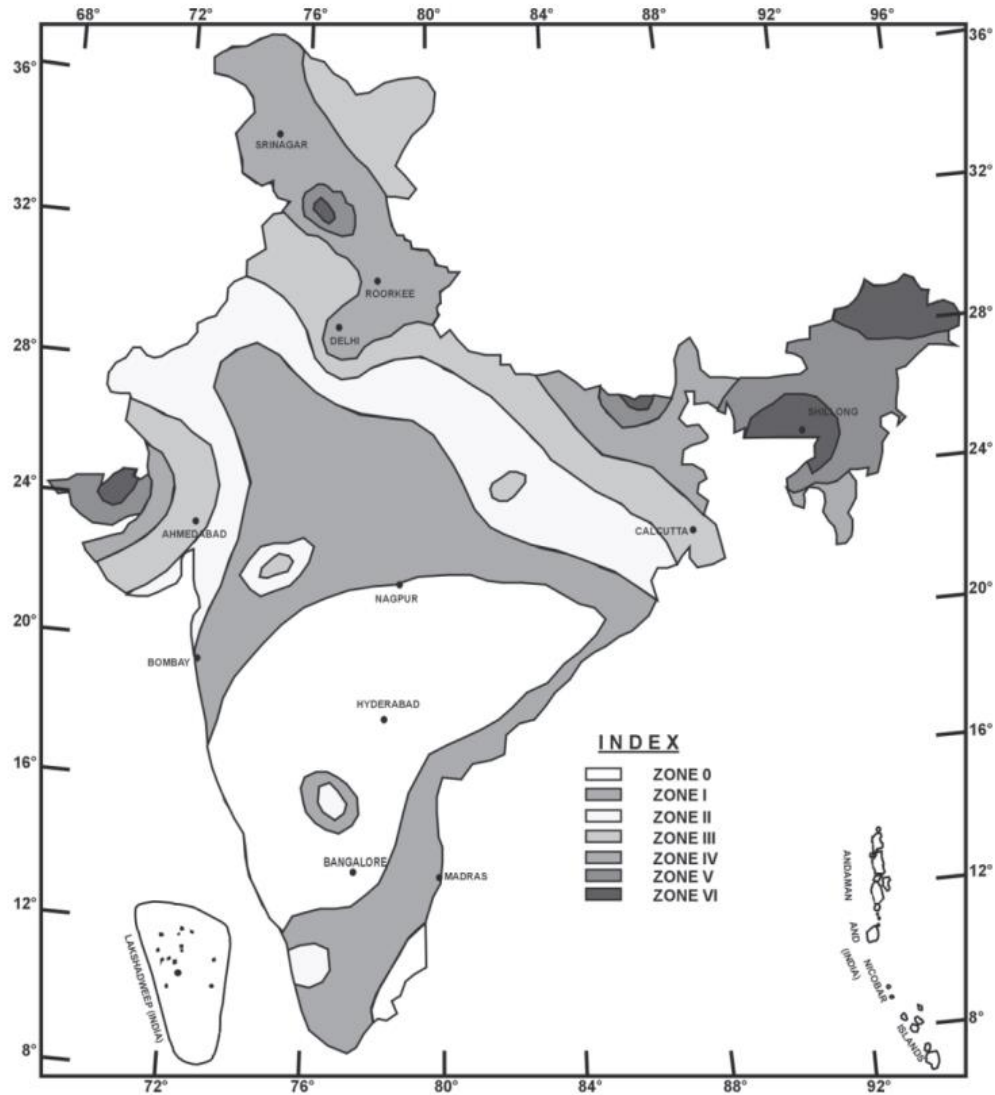


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Fig. 3. Seismic zone map of India (IS 1893, 1962).

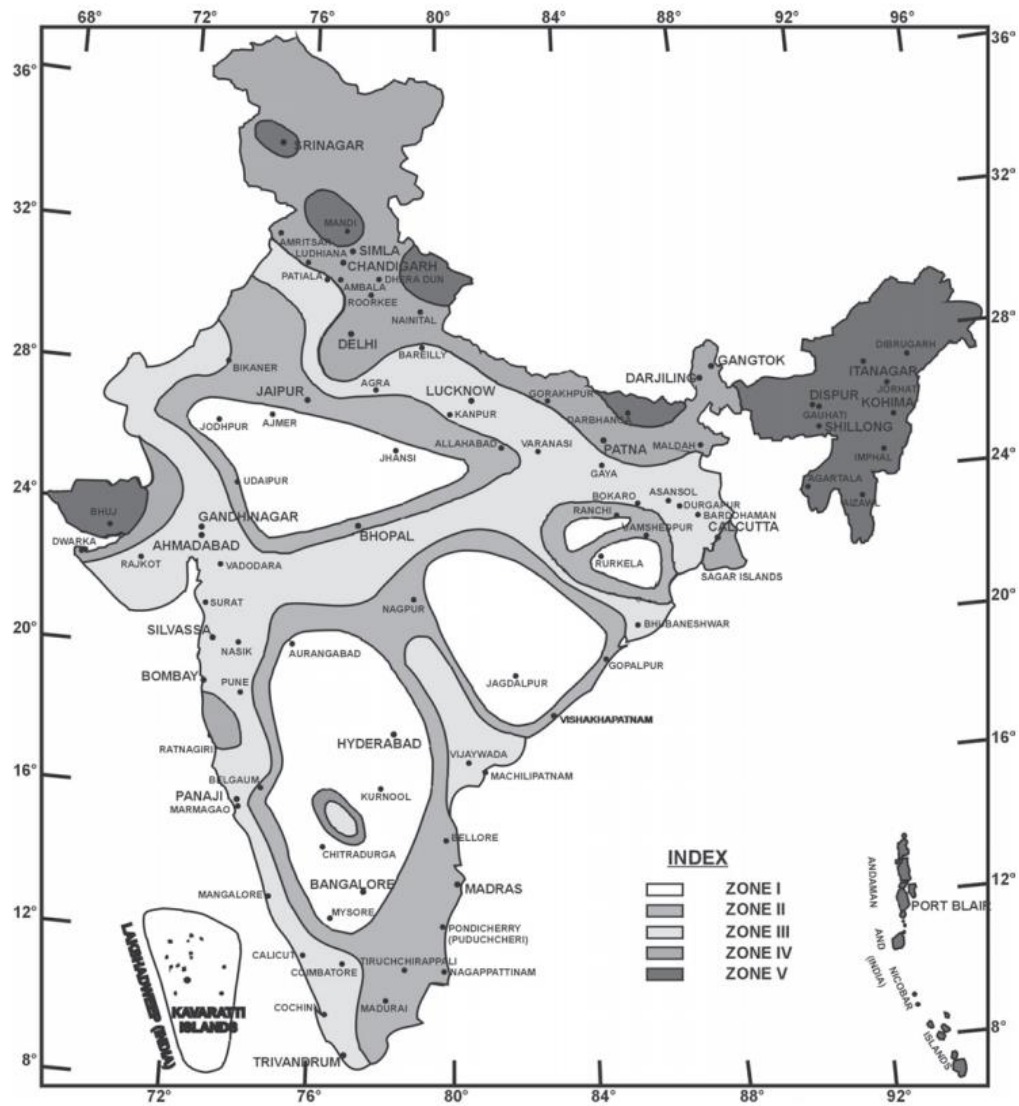
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205
206 **Fig. 4.** Seismic zone map of India (IS 1893, 1966).
207

208 The 1993 Latur earthquake, registering a body wave magnitude (M_b) of 6.3, caused severe
209 destruction with an intensity of IX on the MSK scale. Remarkably, Latur had previously been
210 placed in Seismic Zone I, where the occurrence of such a powerful earthquake was considered
211 unlikely. This surprising event, along with subsequent damaging earthquakes such as the 1997
212 Jabalpur quake (M_b 6.0) and the 2001 Bhuj earthquake (M_w 7.6), raised serious concerns about the
213 adequacy and accuracy of the existing seismic zonation system for Peninsular India. These events

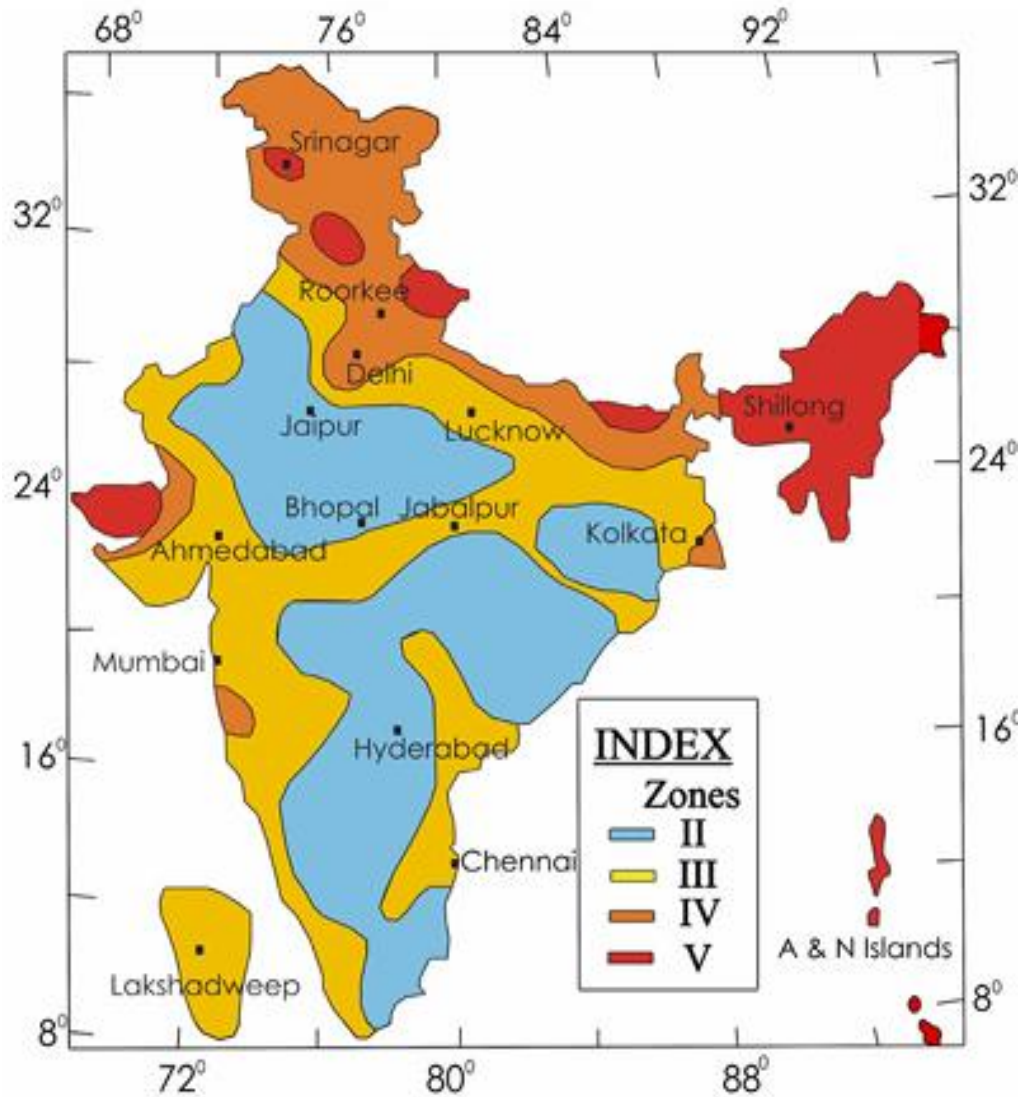
214 prompted a reassessment of the seismic hazard classification, leading to the publication of a revised
215 seismic zonation map in 2002 (IS1893 Part 1, 2002), where the number of zones was reduced to
216 four, namely Zones II, III, IV, and V (Fig. 6).
217



218
219 **Fig. 5.** Seismic zone map of India (IS 1893, 1970).

220
221 The seismic zonation map presented in IS 1893 Part 1 (2016), as shown in Fig. 1a, introduced
222 modification over the earlier IS 1893 Part 1 (2002) version, while continuing with the four-zone

223 classification system Zones II, III, IV, and V. One of the major improvements in BIS 2016 was
224 the inclusion of updated seismic data and enhanced understanding of tectonic features across India,
225 which resulted in refined and more accurate delineation of seismic zones. Although the zone
226 factors remained consistent with the previous version (ranging from 0.10 in Zone II to 0.36 in Zone
227 V), BIS 2016 adopted a more performance-based design approach, emphasizing the use of
228 dynamic analysis in structural design. Greater attention was given to local site conditions, soil
229 profiles, and structural irregularities to improve the safety and effectiveness of earthquake-resistant
230 designs.



232 **Fig. 6.** Seismic zonation map of India prepared in 2002 (IS 1893 Part 1, 2002). The zones I and
233 II are merged to form four zones.

234 The changes made to seismic zonation map of India in response to major earthquake events
235 indicate that hazard assessments conducted at a regional scale often fail to capture localized
236 variations in seismic risk. The zonation map reflects the current state of knowledge regarding
237 seismic activity and the methodologies employed in its assessment. However, it is essential to
238 recognize that this map is not absolute or final, it must be periodically reviewed and revised to
239 incorporate new data, improved analytical techniques, and a deeper understanding of local seismic
240 behavior, while macro-level seismic zonation provides a broader understanding, a more granular
241 perspective is offered through microzonation studies. In this regard, IS 1893 is currently
242 undergoing revision to deliver an updated seismic hazard zonation map considering the city-level
243 seismic microzonation. In this respect, it becomes more important to contribute to the city-level
244 seismic hazard assessment that would finally aid in the development of updated seismic zonations
245 that could be directly used for engineering practices.

246 **Seismic microzonation: Methodological framework and key steps**

247 Seismic microzonation plays a critical role in minimizing earthquake-related risks and is built upon
248 a multidisciplinary framework that incorporates insights from geology, seismology, geophysics,
249 geotechnical engineering, and structural engineering. Gaining a comprehensive understanding of
250 the region's tectonic framework and geological characteristics is essential for pinpointing potential
251 seismic sources and constructing accurate earthquake hazard models. The process demands
252 detailed field investigations to assess seismic hazards at a granular level, effectively capturing
253 spatial variations in ground response. Performing microzonation studies helps experts assess
254 different risks and, most importantly, assists with city planning by helping forecast outcomes of

255 earthquakes. Apart from this, microzonation maps play a key role in choosing the proper sites for
256 hospitals, fire stations and emergency services. They work to protect buildings and sites of cultural
257 value from being harmed in future earthquakes.

258

259 Seismic microzonation is organized into various classes based on how large the mapping area is
260 and how deeply it is investigated. The Technical Committee on Earthquake Geotechnical
261 Engineering of the International Society of Soil Mechanics and Geotechnical Engineering (TC4-
262 ISSMGE, 1999) classifies a Level I map as the simplest, prepared on a scale varying from
263 1:1000000 to 1:50000. The method depends mainly on stored earthquake information and
264 accessible geological and geomorphological details. Microtremors and simple geotechnical
265 investigations are employed to estimate ground movement in a more detailed way which is
266 represented on a map with a scale of between 1:100000 to 1:10000. A Level III approach covers
267 detailed studies of site materials and ground behavior and maps are made using scales from
268 1:25000 to 1:5000. Each time you go up a level, you get a clearer picture of seismic hazard that is
269 important for engineers. In most cases, seismic zonation takes place in three main stages:

- 270 • **Earthquake source characterization:** During this phase, the region's seismic sources are
271 identified and defined using a seismotectonic map. It provides data needed for analyses to
272 determine ground motion at the bedrock level using deterministic or probabilistic methods..
- 273 • **Site characterization:** Assessment of the site conditions is done using investigations
274 focusing on geology, shape of the land, underground detecting techniques and geotechnical
275 issues. At this stage, factors including topography, the shape of the basin and soil
276 nonlinearity are important to understand the site's response to earthquakes.

277 • **Hazard assessment and data interpretation:** The details received from earlier phases are
278 used to gauge nearby seismic hazards such as the site's seismic reactions, how ground
279 motion may intensify and if liquefaction is possible. With this analysis, urban planners can
280 improve their designs and lower the risks involved.

281 Even though seismic microzonation is useful for finding and labeling site-related seismic hazards,
282 its results are closely linked to the seismic motion that is used in the study. For this reason, we
283 must conduct a detailed analysis of seismic hazards, using either deterministic or probabilistic
284 techniques. The next section explores PSHA and DSHA, the fundamental techniques used to
285 determine seismic loads for each site.

286 **Seismic hazard assessment: Deterministic (DSHA) and probabilistic (PSHA) approaches**

287 To assess the seismic risks in a region, its tectonic situation must be analyzed and then information
288 on earthquakes from old and new sources is brought together in a catalog. Tectonic data is used to
289 draw a detailed tectonic map which includes active tectonic features indicated by overlapping
290 earthquake epicenters from the catalogue. The highest possible magnitude for every identified
291 seismogenic source is estimated by including the length of each fault, how far it ruptures in a quake
292 and the strongest earthquake observed. Moreover, the seismic activity is studied to set return
293 periods for various earthquake levels, supporting seismic risk analysis. Based on the literature
294 review, an accepted method of attenuating ground motion is chosen such as a GMPE, to figure out
295 PGA and S_a . Lastly, hazard maps are produced to show the PGA and S_a inside the region for many
296 return period and exceedance rates. Using response spectra, key urban centers of cities are
297 evaluated to produce earthquake-resistant structures by structural engineers and designers. After
298 calculating the PGA, the region is segmented into seismogenic zones according to a standard

299 method. These activities will rely heavily on a careful earthquake catalogue which can be trusted
300 for detailed analysis of seismic hazard.

301

302 There are two ways to categorize earth-quake data, known as pre-instrumental and instrumental
303 records. Studied through historical chronicles, pre-instrumental records support hazard analysis
304 and are included in resources like the NDMA's record catalogue published in 2010 (NDMA,
305 2010). Alternatively, instrument data is provided by advanced seismological networks made up of
306 organizations like the NDMA, the India Meteorological Department (IMD), the International
307 Seismological Center (ISC-UK) and the United States Geological Survey (USGS). The reliability
308 and accuracy of the earthquake catalogue are secured by proper homogenization, declustering and
309 checking its completeness. Different measuring agencies use different scales to report earthquake
310 magnitudes, but all of these are standardized by homogenization, including moment magnitude
311 (M_w), body wave magnitude (M_b), surface wave magnitude (M_s), local magnitude (M_L) and
312 duration magnitude (M_d). M_w is chosen over the others because it is more reliable at big earthquake
313 levels, since it does not suffer from the same saturation problems as the other scales. The
314 correlation equations created by Scordilis (2006) are used to facilitate uniformity in the catalog,
315 ensuring that measurements from diverse scales can be converting into M_w (refer to Eqns. 1–3).
316 Having a standard approach helps correct inconsistencies and guarantees that different datasets
317 function well together.

318
$$M_w = 0.85 M_b + 1.03, \quad \text{for } 3.5 \leq M_b \leq 6.2 \quad (1)$$

319
$$M_w = 0.67 M_s + 2.07, \quad \text{for } 3.0 \leq M_s \leq 6.1 \quad (2)$$

320
$$M_w = 0.99 M_s + 0.08, \quad \text{for } 6.2 \leq M_s \leq 8.2 \quad (3)$$

321 To convert local magnitude (M_L) to moment magnitude (M_w), regional correlations are typically
322 considered more reliable. For India and its surrounding regions, the correlation proposed by
323 Kolathayar et al. (2012) is adopted (Eqn. 4). This region-specific correlation ensures that the
324 conversion best approximates the seismic characteristics of the area, improving the precision of
325 the resulting homogenous earthquake catalogue.

$$326 \quad M_w = 0.815 M_L + 0.767, \quad \text{for } 3.3 \leq M_L \leq 7.0 \quad (4)$$

327 Looking at seismicity over a long period helps remove dependent events like foreshocks and
328 aftershocks which can affect the way seismic hazard is evaluated. Many methods to remove
329 clustering have been described such as the models designed by Gardner and Knopoff (1974) and
330 Reasenber (1985). In addition, checking for completeness is necessary to ensure the dataset
331 results are properly used. Because instruments for recording earthquakes became widespread in
332 1900 and in India in 1960, completeness analysis allows us to assess if the data adequately covers
333 the history of earthquakes. Evaluating the completeness of the catalogue includes checking it with
334 tools and techniques developed in 1985 by Tinti and Mulargia (known as CUVI) and in 1972 by
335 Stepp. As a result, the earthquake record becomes a key resource for figuring out seismic hazards
336 and handling earthquake risks. Beyond these foundational elements, the characterization of
337 earthquake sources involves creating a tectonic map, identifying potential sources of damaging
338 earthquakes, analyzing maximum observed magnitudes (M_{obs}), evaluating total fault lengths (TFL)
339 and focal depths, and estimating the maximum magnitude potential (M_{max}) of seismogenic sources.

340

341 Data from GSI (2000) and USGS was used to prepare the seismotectonic map for the study area
342 Itanagar, Arunachal Pradesh (Fig. 7). North of the region, the Main Frontal Thrust (MFT), Main
343 Boundary Thrust (MBT) and Main Central Thrust (MCT) are major faults with northward-dipping

344 listric geometries. The MFT which is another name for the Himalayan Frontal Thrust (HFT), is
345 the southmost geological boundary of the Himalayas containing the Brahmaputra basin in the north
346 and the Outer Sub-Himalayan belt in the south. Northward, the MBT divides the Outer Sub-
347 Himalayas from the Lesser Himalayas and the MCT outlines the northern extent of the Lesser
348 Himalayas (as Kayal reported in 2008 and Gupta and Biswas stated in 2022). Important tectonic
349 features in this region include the Mishmi Thrust, Lohit Thrust and the Po-Chu Fault, a northwest-
350 southeast trending fault that causes a lateral shift to the right. Between the east and northeast, the
351 Naga Thrust and Disang Thrust which trend northeast-southwest, form an important set of
352 structures that mark the southeastern border of the Brahmaputra Valley. Because of the MCT,
353 MFT, Lohit Thrust and Mishmi Thrust, Arunachal Pradesh and areas close by have experienced
354 unusually strong earthquakes (Das et al., 2006).

355

368 PSHA, using the result of the previous section, provides a way to handle uncertainty in earthquakes
369 and supplies a detailed risk assessment for an area. The methodology includes five main steps: (a)
370 identifying and describing what creates earthquakes, (b) estimating the typical time between
371 earthquakes of various sizes, (c) measuring the distances from the earthquake source to the site
372 and their distribution, (d) calculating PGA and S_a ground motion values and (e) noting the
373 uncertainties in the size, location and intensity of earthquakes (Kramer 1996). Because there are
374 uncertainties with models, the logic tree approach is chosen to weigh and rank various models
375 (Anbazhagan et al. 2019). This method is successful, though it depends on expert choice which
376 adds some subjective aspects to choosing a model. Unlike deterministic methods that focus solely
377 on worst-case scenarios (McGuire 2001a), PSHA provides probabilistic estimates of ground
378 motion intensities, allowing engineers to design structures with an acceptable level of risk. The
379 accuracy of PSHA, however, depends significantly on the availability of a statistically robust
380 earthquake catalogue and well-defined tectonic features, which can be challenging in regions like
381 Western Canada, the Northwestern United States, and parts of India. PSHA initially introduced by
382 Cornell in 1968, has undergone significant advancements through the development of various
383 computational platforms. These include EQRISK (McGuire, 1976), FRISK (McGuire, 1978), its
384 updated version FRISK 88M (McGuire, 2001), OpenSHA (Field et al., 2003), OPENQUAKE
385 (Pagani et al., 2014), and R-CRISIS (Ordaz & Salgado-Gálvez, 2017). Despite its complexity,
386 PSHA remains a critical tool for seismic hazard analysis, supporting engineers and planners in
387 making informed decisions for earthquake-resistant designs. In India, several important studies
388 have applied PSHA, as summarized in Table 1, demonstrating its relevance to local seismic risk
389 assessments. While microzonation offers spatial granularity in hazard zoning, a robust
390 understanding of seismic input motion often derived through PSHA or DSHA is essential for

391 reliable site-specific analysis. This foundational requirement leads us to site characterization
 392 techniques, which are explored in the following sections.

393 **Table. 1** Overview of significant seismic hazard studies conducted in India

Region	Seismic zone as per IS 1893 Part 1 (2016)	PGA (g) as per IS 1893 Part 1 (2016)	PGA (g) as per seismic hazard analysis	Authors
Chennai	III	0.16	0.106	Boominathan et al. (2008)
Bangalore	II	0.1	0.121	Anbazhagan et al. (2009)
South India	II-IV	0.1 - 0.24	0.37	Vipin et al. (2009)
NW Himalaya and its adjoining area	IV to V	0.24 - 0.36	0.50 - 0.7	Mahajan et al. (2010)
Gujarat	III to V	0.16 - 0.36	0.05 - 0.92	Chopra et al. (2012)
Kolkata	III	0.16	0.12 - 0.6	Shiuly and Narayan (2012)
Surat	III	0.16	0.1	Thaker et al. (2012)
Andaman and Nicobar	IV	0.24	0.27 - 0.58	Kataria et al. (2013)
Himachal Pradesh and adjoining areas	IV to V	0.24 - 0.36	0.09 - 0.26	Patil et al. (2014)
Delhi-NCR	IV	0.24	0.15 - 0.23	Rao and Rathod (2014)
Tripura and Mizoram	V	0.36	0.03 - 0.54	Sitharam and Sil (2014)
Patna	IV	0.24	0.03 - 0.44	Anbazhagan et al. (2015)
Goa	III	0.16	0.33 - 0.62	Naik and Choudhury (2015)
Agartala	V	0.36	0.18 - 0.46	Sil and Sitharam (2016)
West Bengal	II to V	0.1 - 0.36	0.11 - 0.45	Maiti et al. (2017)
Guwahati	V	0.36	0.46–0.92	Bahuguna and Sil (2020)
Shillong	V	0.36	0.61–0.83	Agrawal et al. (2023)

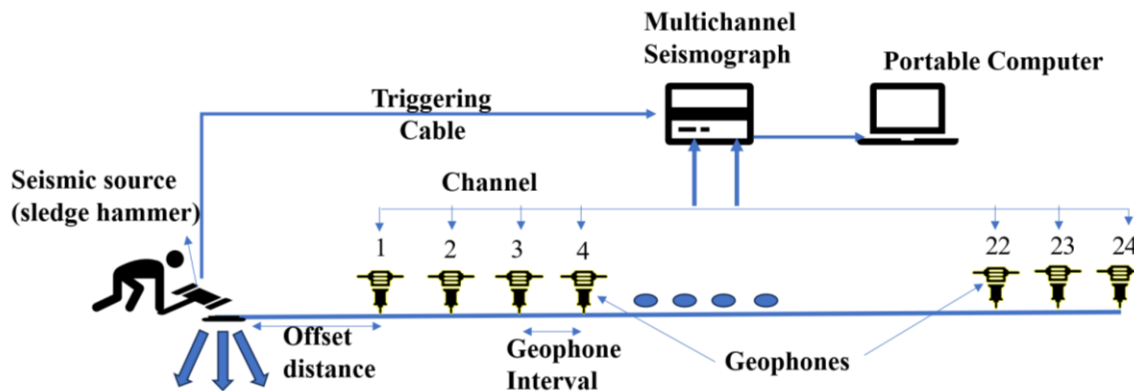
394 **Site characterization: Implications for seismic hazard studies**

395 Site characterization for seismic hazard studies crucially depends on various in-situ field tests used
396 for site characterization. Several commonly adopted methods are used to assess subsurface
397 conditions, including the Standard Penetration Test (SPT), Cone Penetration Test (CPT), Seismic
398 Cone Penetration Test (SCPT), Spectral Analysis of Surface Waves (SASW), P and S wave
399 logging, and Multichannel Analysis of Surface Waves (MASW). Among these, the use of V_{s30} ,
400 which represents the average shear wave velocity in the top 30 meters of soil, is widely recognized
401 for site characterization. In situations where direct measurements of shear wave velocity are not
402 available, V_{s30} values can be estimated from SPT and CPT data using established empirical
403 correlations. The insights gained from the estimates are used to place sites into their respective
404 categories. Geotechnical investigations usually consist of drilling, sampling at selected points and
405 executing tests both on-site and in a laboratory. This method fits well the exploration of smaller
406 areas of soil and rock. However, since seismic microzonation involves vast exploration, it is
407 commonly beyond the scope of usual geotechnical practices. To overcome this, geophysical
408 techniques provide a faster way and handle additional obstacles found in traditional inspection
409 methods. A range of geophysical techniques exist today, many of which give us a continuous view
410 of the subsurface. Certain methods supply details about the rigidity of the ground which proves
411 useful for seismic microzonation work. Such tools further help experts find underground features
412 like cavities, old mine tunnels, faults and discontinuous zones. A main step in seismic
413 microzonation is to obtain detailed information on the subsurface for a wide area. Exploring
414 geotechnical features over such wide areas is very demanding logistically and very expensive. The
415 only practical option for assessing lateral changes in materials near the surface is geophysical
416 exploration which cuts costs. They allow for the testing of how materials near the top of the ground
417 at a site vary side to side. SASW (Stokoe et al., 1989; Foti, 2000) and MASW (Park et al., 1999;

418 Xia et al., 1999) were developed to obtain shear wave velocity profiles by analyzing surface waves.
419 In recent years, many geotechnical earthquake researchers have started to use shear wave velocity
420 distribution (Foti and Butcher, 2004; Socco and Strobbia, 2004; Xia et al., 2004). While both
421 techniques capture subsurface velocity profiles, MASW is preferred because it is more efficient.
422 For large areas, SASW testing is less simple and needs more work since it requires only two
423 geophones.

424
425 The equipment used for active MASW surveys comprises an energy source, receivers, and a Data
426 Acquisition System (DAQ) to facilitate efficient data collection and processing. The energy source
427 produces controlled seismic waves, which are detected by geophones arranged in a specific
428 configuration. Two primary types of energy sources are utilized: impulsive sources (e.g., hammers,
429 weight drops, seismic guns, and explosives) and vibrating sources (e.g., electromechanical
430 vibrators). In this particular study, a 10 kg sledgehammer with an aluminum base plate served as
431 the impact source, chosen for its practicality and effectiveness in generating high-frequency waves.
432 The geophones, which act as receivers, convert mechanical vibrations into electrical signals. For
433 reliable data acquisition, 4.5 Hz geophones were employed. The DAQ seismograph processed the
434 captured signals by filtering and digitizing the waveforms for further analysis. The aluminum
435 striker/base plate improved the transmission of high-frequency components, ensuring efficient
436 energy transfer. Additionally, seismic cables with evenly spaced connection points connected the
437 geophones to the DAQ system, enabling seamless and efficient data transfer. A schematic diagram
438 illustrating how the field setup and data are obtained for an active MASW test is shown in Figure
439 8. To get the surface wave components, the seismic signals are analyzed using an organized and
440 sequential approach. The measured field data is changed into a dispersion curve to look at the

441 variation of shear wave velocity (V_s) as a function of depth. After that, the curve is transformed
 442 back to understand the internal arrangement of the soil. Reducing data noise and highlighting
 443 important signals is done by using techniques known as temporal muting and frequency filtering
 444 (Taipodia and Dey, 2017a, 2017b, 2018; Taipodia et al., 2017, 2020). Performing all the steps
 445 results in cartographic dispersions of fine resolution (Park et al., 1998; Taipodia et al., 2017b,
 446 2018). Using refined pictures, the main dispersion curve with the highest local energy can be
 447 obtained which is important for further study (Taipodia et al. 2019, 2020). The dependence
 448 between phase velocities and frequency variations in the fundamental mode dispersion curve is
 449 explored, with the analyzed curve becoming key data for the final analysis. To do this, we use the
 450 inversion method described by Xia et al. (1999) which draws data from the main mode dispersion
 451 and provides an inverted shear wave velocity (SWV) profile column at diverse depths. SWV is
 452 very important in geotechnics and engineering, helping to confirm the stiffness of soils below
 453 ground which supports the planning of structures and foundations.



454
 455 **Fig. 8.** Schematic diagram of a typical field experimental setup and data acquisition for active
 456 MASW test.

457 The seismic classification of a site depends on soil properties down to 30 meters, according to the
 458 National Earthquake Hazard Reduction Program (BSSC, 2020) and the International Building

459 Code (2000, 2006). Worldwide, the scientific community has widely accepted these systems which
 460 are the main basis for many seismic design rules and handbooks (NEHRP BSSC, 2000; Dobry et
 461 al., 2000; Kanli et al., 2006). As explained in these standards, engineers use shear wave velocity
 462 (V_s), Standard Penetration Test (SPT-N) results and undrained shear strength for classifying sites.
 463 Many researchers have emphasized how V_s are an important part of site characterization and
 464 response studies (Seed et al. 1976; Idriss 1990, 2008; Boore and Joyner 1997; Joyner and Boore
 465 1981; Joyner and Fumal 1984; Presti et al. 2004). The system for classifying seismic sites is based
 466 on the average shear wave velocity in the top 30 meters of subsurface soil which is defined in
 467 Equation (1).

$$468 \quad V_{s30} = \frac{30}{\sum_{i=1}^N \left(\frac{h_i}{v_{si}} \right)} \quad (6)$$

469 where h_i is the thickness of individual soil layers up to the cumulative depth, v_{si} is the shear wave
 470 velocity of the corresponding individual layers and N is the number of individual soil layers within
 471 the depth of 30 m. For seismic site classification, NEHRP BSSC (2020) has suggested to consider
 472 the SWV of the soil within the depth of 30 m (i.e., V_{s30}) from surface level for characterizing the
 473 seismic site response and identifying the seismic parameters required for the design of earthquake
 474 resilient structures at regional scale. According to the updated guidelines (NEHRP BSSC 2020),
 475 depending on V_{s30} , apart from soil sites being classified into six classes as earlier (namely site class
 476 A, B, C, D, E and F), additional three new site classes (BC, CD and DE) are introduced to provide
 477 better insight of the site shear wave velocity classes as shown in Table 2.

478 **Table 2.** Site classification according to local ground conditions defined by NEHRP BSSC (2020)

Site Class	Description of Soil Layers	NEHRP BSSC (2020)
------------	----------------------------	-------------------

		V_{s30} (m/s)
A	Hard rock	> 1500
B	Medium hard rock	> 900 to 1500
BC	Soft rock	> 700 to 900
C	Very dense sand or hard clay	> 480 to 700
CD	Dense sand or very stiff clay	> 330 to 480
D	Medium dense sand or stiff clay	> 230 to 330
DE	Loose sand or medium stiff clay	> 170 to 230
E	Very loose sand or soft clay	< 170
F	Soils requiring site response analysis as per Section 21.1	Ref. Section 20.2.1

479

480 Mahajan et al. (2007) utilized the MASW test to analyze variations in vertical and horizontal shear
481 wave velocities in the Dehradun region. As per NEHRP guidelines (Table 2), Dehradun has been
482 categorized under Site Class 'D' and Class 'C' depending on the average shear wave velocity.
483 Furthermore, spectral acceleration curves for the city were developed for different time periods,
484 considering a damping ratio of 5%. In the Bangalore Mahanagar Palika (BMP) region,
485 Anbazhagan and Sitharam (2008) conducted site classification based on the average shear wave
486 velocity profile. Most of the BMP area was categorized as Class 'C' and Class 'D' according to
487 NEHRP site classification, with the profiles generated from 58 MASW tests. Similarly, Satyam
488 and Rao (2008) performed seismic site characterization for Delhi using the MASW technique at
489 118 locations. The V_{s30} values for areas such as Jawaharlal Nehru University (JNU), Vasanth Kunj,

490 Ladha Sarai, Jarera, and Nangloi Sayied ranged between 400 and 480 m/s, with stiff rock layers
491 identified up to 30 meters in depth. Hanumantharao and Ramana (2009) applied the SASW test to
492 quantify shear wave velocity profiles at 80 sites in the Delhi region. They further developed
493 correlations between V_s and SPT- N values for the same region. Additional tests using remolded
494 sand-silt samples in triaxial cyclic loading were conducted to support the main results, resulting in
495 reduction modulus and damping curves. Maheshwari et al. (2010) analyzed data from 300
496 boreholes and ran 20 MASW tests in Chennai to build a link between shear wave velocity (V_s) and
497 both raw and energy-corrected SPT- N readings. A site classification map for Chennai was also
498 prepared according to the NEHRP standards, while the time periods of different buildings were
499 approximated by using empirical formulas relating height to age. It became clear that low-rise
500 structures in Chennai are more likely to be damaged by earthquakes. Using data from 400
501 boreholes, Mhaske and Chaudhary (2011) built an average V_s model for Mumbai and checked its
502 performance with correlations used in other Indian cities. In the same way, Anbazhagan et al.
503 (2013) did seismic site classifications for Lucknow according to NEHRP rules. In order to correlate
504 V_s and SPT- N values for the Indo-Gangetic Basin, MASW tests were done on 47 sites together
505 with the drilling of 23 boreholes. The site classification by NEHRP shows that most of Lucknow
506 belongs to Class D and a few areas fall into Class C. In Agartala, 27 landslide sites were examined
507 with the MASW method by both Sil and Sitharam (2014). Both the Q-Q plot and existing regional
508 correlations were used to match shear wave velocity (V_s) with SPT- N values. According to the V_s
509 and SPT- N results, Agartala was mostly placed in Site Classes D and E. At 42 sites, Thokchom et
510 al. (2017) used MASW, while P-S logging was carried out at 16 locations in Dholera, Gujarat, to
511 analyze shear wave velocity. In the Kumaon Himalayas, Joshi and Bhardwaj (2018) used the
512 MASW approach to ascertain shear wave velocity, changing the frequency from 1.01 Hz up to

513 5.94 Hz. MASW measurements were also used by Chakraborty et al. (2018) for geophysical study
514 in Jaipur to figure out shear wave velocity. They found that these areas could be categorized as
515 Class C or Class D by the NEHRP standard. To examine two Indian ash pond sites, Parhi et al.
516 (2020) applied MASW research to measure shear wave velocity. On the abandoned ash pond at
517 NTPC Korba, we detected a mean V_s surface value of 149 m/s and a depth value of 203 m/s at 20
518 meters below the surface. In the abandoned pond at VTPS Vijayawada, the wind values were 161
519 m/s and 245 m/s. Nagamani et al. (2020) carried out a site characterization in the southern Gujarat
520 mainland region, estimating the shear velocity profiles up to 100 m using ellipticity inversion.
521 From the results of the geotechnical investigation, V_{s30} values in the area were shown to lie between
522 520 and 1350 m/s. Kumar et al. (2022) reported that shear wave velocity and SPT-N responses in
523 the city of Amaravati are connected. Data from 25–45m deep boreholes was studied together with
524 information from 30 microtremor stations. The study showed that the Amaravati region should be
525 classified as Class D in accordance with the NEHRP BSSC (2003) rules. Ansari et al. (2024)
526 completed a detailed seismic microzonation of the Jammu region, using both deterministic and
527 probabilistic seismic analysis to draw boundaries encompassing regions of various seismic risks
528 such as those based on shear-wave velocity (V_s) and high/low-frequency properties. At all 242
529 testing sites, various geophysical processes revealed three categories of hazard zones (low,
530 moderate and high) which were applied to determine the vulnerability of the USBRL railway
531 project. Aas and Sinha (2023) carried out seismic site characterization at twelve points within the
532 southern foothills of the Himalayas using MASW measurements. The V_{s30} values for the studied
533 area were found to range between 285 and 375 m/s. Based on these shear wave velocity values,
534 the entire foothills region was classified as Site Class C or Site Class D under NEHRP guidelines.
535 A breakdown of classified sites in different Indian cities, found from MASW studies and based on

536 NEHRP requirements, is presented in Table 3. Detailed characterization of the site provides key
 537 data that is essential for soil and structure analysis and earthquake response simulation, as will be
 538 covered in the following section..

539 **Table 3.** A summary of site characterization for Indian cities based on SWV from MASW tests

References	City	V_s / Site-classes
Satyam and Rao (2008)	Delhi	V_s - 185 to 495 m/s
Mahajan (2009)	Dehradun	Site-class C, D and E
Kumar et al. (2010)	Lucknow	Site class- C and D
Maheswari, et al. (2010)	Chennai	Site class-D
Rao et al. (2011)	Jabalpur	V_s - 250 to 750 m/s
Sil and Sitharam (2014)	Agartala	Site class- D and E
Chakraborty et al. (2018)	Jaipur	Site Class- C and D
Sairam et al. (2018)	Ahmedabad	V_s - 260–360 m/s, Site class- D
Saha et al. (2021)	Silchar	Site class- D
Singh et al. (2021)	Varanasi	V_s - 310 to 690 m/s, Site class- C and D
Imam et al. (2023)	Jamshedpur	V_s - 402m/s, Site class-C

540

541 **Ground response analysis: Equivalent-linear and nonlinear approaches**

542 In geotechnical earthquake engineering, one of the most essential and commonly required
 543 assessments is the evaluation of ground response during seismic events. The purpose of this
 544 analysis is to evaluate how seismic waves are amplified or attenuated, develop response spectra,
 545 identify peak ground accelerations and associated resonant frequencies, analyse deformation
 546 behavior for liquefaction assessment, and estimate seismic loads acting on embankment dams.
 547 Various techniques can be used to estimate wave amplification, including linear and equivalent
 548 linear as well as nonlinear approaches in either 1D, 2D or 3D environments. The nonlinear
 549 hysteretic behavior of soils is simplified in linear form by Schnabel et al. (1972), a method used to
 550 develop the SHAKE program. This computer program is widely used for 1D equivalent linear

551 ground response analysis. However, since soil exhibits nonlinear behavior, its shear modulus
552 continuously changes under cyclic loading. Several researchers, including Liam Finn et al. (1978),
553 Arslan and Siyahi (2006), Hosseini and Pajouh (2012), and Kramer (1996), have highlighted the
554 limitations of the equivalent linear approach in capturing real-time changes in soil stiffness.
555 Results from different investigations indicate that nonlinear models provide a better understanding
556 of how soil behaves under earthquake loads (Hosseini and Pajouh, 2012). Besides, where the
557 ground has deep, soft layers or if there is expected strong seismic risk, the equivalent linear method
558 is often thought to not be reliable (Hashash et al., 2010). For this reason, most researchers choose
559 the nonlinear approach when analyzing ground response. Researchers such as Ramberg and
560 Osgood (1943), Matasovic and Vucetic (1993) and Hashash and Park (2001) have introduced a
561 range of nonlinear models that are now often used. Seismic wave amplification is most commonly
562 examined using a one-dimensional approach, which assumes that horizontal shear waves
563 propagate vertically from the bedrock through successive soil layers. However, in complex
564 scenarios requiring two- or three-dimensional analysis, more sophisticated constitutive models are
565 employed. Notable contributions in this area include those by Mroz (1967), Momen and Ghaboussi
566 (1982), Dafalias (1986), Kabilamany and Ishihara (1990), Gutierrez et al. (1993), and Cubrinovski
567 and Ishihara (1998).

568
569 Due to its simplicity, equivalent-linear analysis has been extensively utilized across India for
570 ground response studies. Notable examples include the ground response analysis of Bhuj (Sitharam
571 and Govindaraju, 2004), Chennai (Boominathan et al., 2008), Bangalore (Anbazhagan and
572 Sitharam, 2009), Kolkata (Govindaraju and Bhattacharya, 2012), Kanpur (Jishnu et al., 2013),
573 Delhi (Mandal et al., 2014), Mumbai Nuclear Power Plant and Port (Desai and Choudhury, 2015),

574 Mumbai city (Choudhury et al., 2015), Kolkata (Chatterjee and Choudhury, 2016), Uttarakhand
575 (Pandey et al., 2016), Dhanbad (Gupta et al., 2023), Itanagar (Anshu et al., 2024). Over time, the
576 nonlinear method has advanced significantly, allowing for a more accurate representation of the
577 nonlinear behavior of soil (Stewart and Kwok, 2008). However, due to the complexity involved in
578 selecting input parameters, nonlinear ground response analyses have been relatively rare
579 worldwide. Some notable studies include New Madrid (Zheng and Luna, 2011), Bam (Rayhani et
580 al., 2008), Turkey (Kwok et al., 2008), Southern Switzerland (Roten et al., 2009), Chennai (Uma
581 Maheshwari et al., 2010), Amingaon (Kumar et al., 2014), Guwahati (Dammala et al., 2017) and
582 Bihar (Kumari et al., 2024). Various computer programs are available for conducting ground
583 response analysis. These software tools calculate the tangent shear modulus, which reflects the
584 actual nonlinear behavior of soils, and solve the dynamic motion equations within the time domain
585 using incremental time integration methods. Despite sharing this fundamental approach, they differ
586 in how they model nonlinear soil response and incorporate material damping. Among the most
587 frequently used nonlinear ground response analysis tools are D-MOD2000 (Matasović and
588 Ordóñez, 2007), DEEPSOIL (Hashash et al., 2015), OpenSees (Mazzoni et al., 2006), SUMDES
589 (Li et al., 1992), and TESS (Pyke, 2000). While all of these can conduct one-dimensional nonlinear
590 analyses, OpenSees and SUMDES are also equipped to handle two- and three-dimensional ground
591 motion simulations.

592

593 DEEPSOIL has recently emerged as one of the most widely used open-source tools for performing
594 one-dimensional equivalent linear ground response analysis (GRA). For this analysis, input
595 parameters typically include the shear wave velocity or the small-strain shear modulus and the unit
596 weight for each layer of soil. After specifying the soil stratigraphy and associated properties, the

597 only other major requirement is the input ground motion. This motion is generally provided as an
 598 acceleration time history, either at an assumed bedrock outcrop (commonly used due to
 599 compatibility with ground motion prediction models) or at the bedrock-soil interface beneath the
 600 soil column. The output from the analysis includes shear stress, shear strain, and acceleration time
 601 histories, along with peak values recorded at the surface, the assumed outcrop bedrock, and at
 602 various depths within the soil layers. Table 4 provides a compilation of earlier studies that have
 603 utilized DEEPSOIL.

604

605 **Table 4.** Overview of previous studies on site response analysis of Indian cities.

Region	Seismic zone as per IS 1893 Part 1 (2016)	PGA (g) as per IS 1893 Part 1 (2016)	Maximum amplification factor	Calculated PGA (g)	Authors
Bangalore	II	0.1	1.0 - 4.90	0.01 - 0.66	Anbazhagan and Sitharam (2009)
Kutch (Gujarat)	V	0.36	2.45	0.22	Thaker et al. (2010)
Kolkata	III	0.16	1.88 - 2.07	0.22 - 0.27	Govindaraju and Bhattacharya (2012)
Surat (Gujarat)	III	0.16	2.1	0.21	Thaker et al. (2012)
Panjim City	III	0.16	1.56 - 2.36	0.17 - 0.25	Naik and Choudhury (2013)
Guwahati City	V	0.36	1.2 - 1.7	0.2 - 0.79	Kumar and Krishna (2013)
Delhi	IV	0.24	1.8	0.23 - 0.27	Rao and Rathod (2014)
Mumbai	III	0.16	1.0 - 4.0	0.07 - 0.213	Desai and Choudhury (2015)
Vijayawada	III	0.16	0.71	0.27	Satyam and Towhata (2016)

606
607 The extent of seismic amplification or attenuation in an area is primarily influenced by the dynamic
608 characteristics of the underlying soil. Therefore, determining these properties is a crucial step in
609 addressing geotechnical earthquake engineering challenges and conducting ground response
610 analysis (GRA) studies. Moreover, dynamic soil properties are extensively used to evaluate the
611 interaction between earthquake forces and the soil mass in the selected area. Key dynamic
612 properties include the shear modulus (G), modulus reduction (G/G_{max}) curves, and the variation of
613 damping ratio (ζ) with cyclic strains. Additional parameters essential for conducting GRA include
614 the thickness of each soil layer, density, shear wave velocity (V_s), and input ground motion. Among
615 these, density plays a significant role in determining the low-strain shear modulus of subsurface
616 soil layers. Hanumantharao and Ramana (2008) classified the soils in their study as either fine-
617 grained or coarse-grained. The required density parameters were obtained in accordance with IS:
618 2720 Part 29 (1975). Determining soil density in the field is often a lengthy process and may
619 introduce minor inaccuracies. Even small deviations in density can lead to variations in the peak
620 spectral acceleration, typically within the range of 0.05g to 0.1g. Nevertheless, these fluctuations
621 have a negligible effect on the calculated predominant period and spectral amplification values
622 (Hanumantharao and Ramana, 2008). As a result, assumed density values are only applied in rare
623 cases during ground response analysis.

624
625 An essential step in ground response analysis (GRA) is the selection of appropriate strain-
626 dependent G/G_{max} and damping ratio (ζ) curves, which are critical for assessing the nonlinear
627 response of the soil medium. When site-specific G/G_{max} and ζ curves are unavailable, researchers
628 such as Anbazhagan and Sitharam (2008), Phanikanth et al. (2011), Reddy et al. (2021), Kumar

629 and Krishna (2013), Shukla and Choudhury (2012a), and Kamatchi et al. (2008), have conducted
630 GRA using globally developed G/G_{max} and damping ratio curves to estimate site amplification for
631 various cities in India. Barani et al. (2013) examined the influence of G/G_{max} and ζ curves on site
632 amplification and emphasized the importance of their selection in accurately determining the site
633 amplification. Over time, researchers have developed numerous G/G_{max} and damping ratio curves
634 tailored to different shear strain levels and material types. For various soil types, a wide range of
635 G/G_{max} and damping ratio (ζ) curves is notably available in the literature such as those proposed
636 by Seed and Idriss (1970), Seed et al. (1986), Sun et al. (1988), Vucetic and Dobry (1991), Electric
637 Power Research Institute (EPRI, 1993), Ishibashi and Zhang (1993), Rollins et al. (1998),
638 Darendeli (2001), Menq (2003), Zhang et al. (2005, 2008), Kallioğlu et al. (2008), and Chen et
639 al. (2019). These curves are extensively used to describe the dynamic behavior of soil columns.
640 Choosing unsuitable G/G_{max} and ζ curves can introduce substantial inaccuracies in the estimation
641 of response parameters. Anbazhagan et al. (2017b) highlighted this issue by demonstrating how
642 an improper curve selection could result in unreliable response analysis for deep soil sites, based
643 on observations from KiK-Net data.

644

645 Since soil is typically composed of varying particle sizes such as gravel, sand, silt, and clay,
646 accurate classification is essential for assessing its dynamic characteristics. A thorough
647 understanding of how these mixed soils respond to dynamic loads is key to conducting reliable
648 seismic analyses. Hanumanthrao and Ramana (2008) carried out cyclic triaxial tests on samples
649 made by combining Yamuna river sand with non-plastic fines, aiming to investigate the dynamic
650 behavior of such mixtures. Their findings indicated that, for soils lacking plastic fines, the
651 normalized shear modulus reduction (G/G_{max}) and damping ratio (ζ) curves closely matched

652 the lower bound curves proposed by Seed and Idriss (1970). Anbazhagan et al. (2017b) further
653 emphasized that Seed and Idriss (1970) curves are best suited for sandy soils, Rollins et al. (1998)
654 for gravelly soils, and EPRI (1993) curves for rock-like materials. Likewise, a study by Okur and
655 Ansal (2007), following the 1999 Kocaeli earthquake, demonstrated the significant influence of
656 the plasticity index on G/G_{max} and ζ curves behavior in fine-grained soils, aligning with the
657 observations of Vucetic and Dobry (1991).

658

659 **Critical appraisal and the way forward**

660 Seismic microzonation plays a pivotal role in understanding and mitigating earthquake risks,
661 especially in highly vulnerable regions like Itanagar in Arunachal Pradesh. This review
662 consolidates the essential methodologies, tools, and findings associated with seismic hazard
663 assessment and microzonation, underscoring the need for region-specific data and
664 multidisciplinary integration. The study reveals the current state of microzonation practices in
665 India and outlines the key components that determine the success of such initiatives. The critical
666 understanding that can be drawn from this review manuscript are as follows:

- 667 • Seismic hazard analysis using both DSHA and PSHA is fundamental for estimating input
668 ground motion parameters such as PGA and S_a , which are critical for GRA and seismic
669 design.
- 670 • Site characterization, incorporating geological, geophysical, and geotechnical data (e.g.,
671 MASW, SPT), is indispensable for assessing site-specific seismic responses.
- 672 • The selection of suitable G/G_{max} and damping ratio curves greatly influences the accuracy
673 of equivalent-linear and nonlinear GRA models.

- 674 • Microzonation maps, developed from the integration of seismic hazard assessment and site
675 response analysis, are vital for informed urban planning, land-use zoning, and disaster
676 preparedness.
- 677 • There remains a significant gap in high-resolution, region-specific geotechnical data,
678 particularly in the northeastern region of India.
- 679 • Most Indian microzonation studies are at an early stage and require regular updates based
680 on evolving datasets and methodologies.
- 681 • A strong emphasis on multidisciplinary collaboration is necessary to standardize
682 methodologies and enhance the quality of hazard mapping across the country.

683 In conclusion, the transformation of seismic microzonation from a research-based initiative into a
684 practical planning and policy tool demands continuous refinement, localized investigations, and
685 updated hazard models. Strengthening the scientific base of microzonation through reliable ground
686 data and robust analytical techniques will significantly improve earthquake resilience and safety,
687 particularly in high-risk zones like Itanagar. Additionally, seismic microzonation mapping should
688 be seen as a continuous process rather than a completed task, since maps can always be refined
689 and updated as newer and more accurate data become available.

690

691 **Compliance with Ethical Standards**

692 **Conflict of Interest:** On behalf of all authors, the corresponding author declares that there are no
693 conflicts of interest.

694 **Ethical Approval:** This article does not include any studies involving human participants or
695 animals conducted by any of the authors.

696 **Informed Consent:** For this type of study, formal consent is not required.

697 **Author Contributions:** AKA: Formal analysis, Writing – Original preparation; AD:
698 Conceptualization, Revision and Editing of drafted manuscript; SK: Revision and Editing of
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703

704 **References**

- 705 1. Aas, A., and S. K. Sinha. 2023. “Seismic site characterization using MASW and correlation study between
706 shear wave velocity and SPT-N.” *J. Appl. Geophys.* 215: 105–131.
707 <https://doi.org/10.1016/j.jappgeo.2023.105131-1-10>.
- 708 2. Agrawal, N., L. Gupta, J. Dixit, and S. K. Dash. 2023. “Seismic risk assessment for the North Eastern Region
709 of India by integrating seismic hazard and social vulnerability.” *Sustain. Resil. Infrastruct.* 8: 102–132.
710 <https://doi.org/10.1080/23789689.2022.2133764>.
- 711 3. Anbazhagan, P., K. Abhishek, and T. G. Sitharam. 2013. “Seismic site classification and correlation between
712 standard penetration test N value and shear wave velocity for Lucknow city in Indo-Gangetic basin.” *Pure
713 Appl. Geophys.* 170: 299–318. <http://dx.doi.org/10.1007/s00024-012-0525-1>.
- 714 4. Anbazhagan, P., K. Bajaj, N. Dutta, S. S. Moustafa, and N. S. Al-Arifi. 2017a. “Region-specific deterministic
715 and probabilistic seismic hazard analysis of Kanpur city.” *J. Earth Syst. Sci.* 126 (1): 12.
716 <http://dx.doi.org/10.1007/s12040-016-0779-6>.
- 717 5. Anbazhagan, P., K. Bajaj, K. Matharu, S. S. Moustafa, and N. S. Al-Arifi. 2019. “Probabilistic seismic hazard
718 analysis using the logic tree approach—Patna district (India).” *Nat. Hazards Earth Syst. Sci.* 19 (10): 2097–
719 2115. <http://dx.doi.org/10.5194/nhess-19-2097-2019>.
- 720 6. Anbazhagan, P., K. Bajaj, and S. Patel. 2015. “Seismic hazard maps and spectrum for Patna considering
721 region-specific seismotectonic parameters.” *Nat. Hazards* 78: 1163–1195. [http://dx.doi.org/10.1007/s11069-
722 015-1764-0](http://dx.doi.org/10.1007/s11069-015-1764-0).
- 723 7. Anbazhagan, P., A. Prabhakaran, H. Madhura, S. S. R. Moustafa, and N. S. N. Al-Arifi. 2017b. “Selection
724 of representative shear modulus reduction and damping curves for rock, gravel and sand sites from the KiK-
725 Net downhole array.” *Nat. Hazards* 88 (3): 1741–1768. <https://doi.org/10.1007/s11069-017-2944-x>.
- 726 8. Anbazhagan, P., and T. G. Sitharam. 2008. “Seismic microzonation of Bangalore, India.” *J. Earth Syst. Sci.*
727 117 (2): 833–852. <https://doi.org/10.1007/s12040-008-0071-5>.

- 728 9. Anbazhagan, P., and T. G. Sitharam. 2009. "Estimation of ground response parameters and comparison with
729 field measurements." *Indian Geotech. J.* 39 (3): 245–270.
- 730 10. Anbazhagan, P., J. S. Vinod, and T. G. Sitharam. 2009. "Probabilistic seismic hazard analysis for Bangalore."
731 *Nat. Hazards* 48: 145–166. <http://dx.doi.org/10.1007/s11069-008-9253-3>.
- 732 11. Ansari, A., K. S. Rao, and A. K. Jain. 2024. "Seismic microzonation of the Himalayan region considering
733 site characterization: Application toward seismic risk assessment for sustainable tunneling projects." *Nat.*
734 *Hazards Rev.* 25 (1): 04023052. <http://dx.doi.org/10.1061/NHREFO.NHENG-1815>.
- 735 12. Anshu, A. K., J. Taipodia, S. S. Kumar, and A. Dey. 2024. "Identification of ground response parameters of
736 Itanagar City, Arunachal Pradesh, India, using varying seismic intensities and equivalent linear analysis
737 approach." *Indian Geotech. J.*: 1–23. <http://dx.doi.org/10.1007/s40098-024-00967-w>.
- 738 13. Arslan, H., and B. Siyahi. 2006. "A comparative study on linear and nonlinear site response analysis."
739 *Environ. Geol.* 50: 1193–1200. <https://doi.org/10.1007/s00254-006-0291-4>.
- 740 14. Bahuguna, A., and A. Sil. 2020. "Comprehensive seismicity, seismic sources, and seismic hazard assessment
741 of Assam, North East India." *J. Earthq. Eng.* 24 (2): 254–297.
742 <http://dx.doi.org/10.1080/13632469.2018.1453405>.
- 743 15. Barani, S., R. De Ferrari, and G. Ferretti. 2013. "Influence of soil modeling uncertainties on site response."
744 *Earthq. Spectra* 29 (3): 705–732. <https://doi.org/10.1193/1.4000159>.
- 745 16. Boominathan, A., G. R. Dodagoudar, A. Suganthi, and U. R. Maheswari. 2008. "Seismic hazard assessment
746 of Chennai city considering local site effects." *J. Earth Syst. Sci.* 117 (2): 853–863.
747 <http://dx.doi.org/10.1007/s12040-008-0072-4>.
- 748 17. Boore, D. M., and W. B. Joyner. 1997. "Site amplification for generic rock sites." *Bull. Seismol. Soc. Am.*
749 87 (2): 327–341. <https://doi.org/10.1785/BSSA0870020327>.
- 750 18. Borchardt, R. D. 1994. "Estimates of site-dependent response spectra for design (methodology and
751 justification)." *Earthq. Spectra* 10: 617–654. <http://dx.doi.org/10.1193/1.1585791>.
- 752 19. Chakraborty, P., U. Kumar, and V. Puri. 2018. "Seismic site classification and liquefaction hazard
753 assessment of Jaipur City, India." *Indian Geotech. J.* 48: 768–779. [https://doi.org/10.1007/s40098-017-0287-](https://doi.org/10.1007/s40098-017-0287-x)
754 [x](https://doi.org/10.1007/s40098-017-0287-x).
- 755 20. Chatterjee, K., and D. Choudhury. 2016. "Influence of local soil conditions for ground response in Kolkata
756 city during earthquakes." *Proc. Natl. Acad. Sci. India Sect. A Phys. Sci.*: 1–14.
757 <https://doi.org/10.1007/s40010-016-0265-1>.
- 758 21. Chen, G., Z. Zhou, T. Sun, Q. Wu, L. Xu, S. Khoshnevisan, and D. Ling. 2019. "Shear modulus and damping
759 ratio of sand–gravel mixtures over a wide strain range." *J. Earthq. Eng.* 23 (8): 1407–1440.
760 <http://dx.doi.org/10.1080/13632469.2017.1387200>.
- 761 22. Chopra, S., D. Kumar, B. K. Rastogi, P. Choudhury, and R. B. S. Yadav. 2012. "Deterministic seismic
762 scenario for Gujarat region, India." *Nat. Hazards* 60: 517–540. [http://dx.doi.org/10.1007/s11069-011-0027-](http://dx.doi.org/10.1007/s11069-011-0027-y)
763 [y](http://dx.doi.org/10.1007/s11069-011-0027-y).

- 764 23. Choudhury, D., V. S. Phanikanth, S. Y. Mhaske, R. R. Phule, and K. Chatterjee. 2015. "Seismic liquefaction
765 hazard and site response for design of piles in Mumbai city." *Indian Geotech. J.* 45 (1): 62–78.
766 <http://dx.doi.org/10.1007/s40098-014-0108-4>.
- 767 24. Cornell, C. A. 1968. "Engineering seismic risk analysis." *Bull. Seismol. Soc. Am.* 58: 1583–1606.
768 <https://doi.org/10.1785/BSSA0580051583>.
- 769 25. Cubrinovski, M., and K. Ishihara. 1998. "Modelling of sand behaviour based on state concept." *Soils Found.*
770 38 (3): 115–127. https://doi.org/10.3208/sandf.38.3_115.
- 771 26. Dafalias, Y. F. 1986. "Bounding surface plasticity. I: Mathematical foundation and hypoplasticity." *J. Eng.*
772 *Mech.* 112 (9): 966–987. [https://doi.org/10.1061/\(ASCE\)0733-9399\(1986\)112:9\(966\)](https://doi.org/10.1061/(ASCE)0733-9399(1986)112:9(966)).
- 773 27. Dammala, P. K., A. M. Krishna, S. Bhattacharya, G. Nikitas, and M. Rouholamin. 2017. "Dynamic soil
774 properties for seismic ground response studies in northeastern India." *Soil Dyn. Earthq. Eng.* 100: 357–370.
775 <https://doi.org/10.1016/j.soildyn.2017.06.003>.
- 776 28. Darendeli, M. B. 2001. Development of a new family of normalized modulus reduction and material damping
777 curves. Ph.D. diss., University of Texas at Austin. <http://hdl.handle.net/2152/10396>.
- 778 29. Das, S., I. D. Gupta, and V. K. Gupta. 2006. "A probabilistic seismic hazard analysis of Northeast India."
779 *Earthq. Spectra* 22 (1): 1–27. <https://doi.org/10.1193/1.2163914>.
- 780 30. Desai, S. S., and D. Choudhury. 2015. "Site-specific seismic ground response study for nuclear power plants
781 and ports in Mumbai." *Nat. Hazards Rev.* 16 (4): 1–13. [http://dx.doi.org/10.1061/\(ASCE\)NH.1527-
782 6996.0000177](http://dx.doi.org/10.1061/(ASCE)NH.1527-6996.0000177).
- 783 31. Dobry, R., R. D. Borcherdt, C. B. Crouse, I. M. Idriss, W. B. Joyner, G. R. Martin, M. S. Power, E. E. Rinne,
784 and R. B. Seed. 2000. "New site coefficients and site classification system used in recent building seismic
785 code provisions." *Earthq. Spectra* 16: 41–67. <https://doi.org/10.1193/1.1586082>.
- 786 32. Electric Power Research Institute (EPRI). 1993. *Guidelines for Site-Specific Ground Motions*. Palo Alto,
787 California, November, TR-102293.
- 788 33. Emergency Events Database (EM-DAT). <https://public.emdat.be/> (Last Accessed 17.01.2025).
- 789 34. Field, E. H., T. H. Jordan, and C. A. Cornell. 2003. "OpenSHA: A developing community-modeling
790 environment for seismic hazard analysis." *Seismol. Res. Lett.* 74: 406–419.
791 <http://dx.doi.org/10.1785/gssrl.74.4.406>.
- 792 35. Foti, S. 2000. Multistation methods for geotechnical characterization using surface waves. Ph.D. diss.,
793 Politecnico di Torino. <http://dx.doi.org/10.6092/polito/porto/2497212>.
- 794 36. Foti, S., and A. P. Butcher. 2004. "Geophysical methods applied to geotechnical engineering." *Proc. ISC-2*
795 *on Geotechnical and Geophysical Site Characterization*, 409–418.
- 796 37. Gardner, J. K., and L. Knopoff. 1974. "Is the sequence of earthquakes in southern California with aftershocks
797 removed, Poissonian?" *Bull. Seismol. Soc. Am.* 64 (5): 1363–1367.
- 798 38. Giardini, D., G. Grünthal, K. M. Shedlock, and P. Zhang. 1999. "The GSHAP global seismic hazard map."
799 *Ann. Geophys.* 42 (6). <https://doi.org/10.4401/ag-3784>.

- 800 39. Govindaraju, L., and S. Bhattacharya. 2012. "Site-specific earthquake response study for hazard assessment
801 in Kolkata city, India." *Nat. Hazards* 61: 943–965. <http://dx.doi.org/10.1007/s11069-011-9940-3>.
- 802 40. Gupta, R. K., M. Agrawal, R. Shams, and S. K. Pal. 2023. "Seismic site response study of Dhanbad city
803 (India) using equivalent linear analysis complemented by horizontal-to-vertical spectral ratios." *Environ.*
804 *Earth Sci.* 82 (12): 291. <http://dx.doi.org/10.1007/s12665-023-10985-1>.
- 805 41. Gupta, S., and M. Biswas. 2022. "Seismo-tectonic and morphological study of the north-east Himalaya."
806 *Geosci. J.* 27 (1): 1–21. <http://dx.doi.org/10.1007/s12303-022-0016-z>.
- 807 42. Gutenberg, B., and C. F. Richter. 1954. *Seismicity of the earth and associated phenomena*. Princeton
808 University Press. <https://babel.hathitrust.org/cgi/pt?id=uc1.31822009173741>.
- 809 43. Gutierrez, M., K. Ishihara, and I. Towhata. 1993. "Model for the deformation of sand during rotation of
810 principal stress directions." *Soils Found.* 33 (3): 105–117. https://doi.org/10.3208/sandf1972.33.3_105.
- 811 44. Hanumantharao, C., and G. V. Ramana. 2008. "Dynamic soil properties for microzonation of Delhi, India."
812 *J. Earth Syst. Sci.* 117 (2): 719–730. <https://doi.org/10.1007/s12040-008-0066-2>.
- 813 45. Hanumantharao, C., and G. V. Ramana. 2009. "Site-Specific Ground Response Analysis at Delhi, India."
814 *Electron. J. Geotech. Eng.* 14 (D): 1–15.
- 815 46. Hashash, Y. M. A., and D. Park. 2001. "Non-linear one-dimensional seismic ground motion propagation in
816 the Mississippi embayment." *Eng. Geol.* 62 (1–3): 185–206. [https://doi.org/10.1016/S0013-7952\(01\)00061-](https://doi.org/10.1016/S0013-7952(01)00061-8)
817 [8](https://doi.org/10.1016/S0013-7952(01)00061-8).
- 818 47. Hashash, Y. M. A., D. Park, C. C. Tsai, C. Phillips, and D. R. Groholski. 2015. *DEEPSOIL – 1-D wave*
819 *propagation analysis program for geotechnical site response analysis of deep soil deposits, version 6.1.*
820 *Tutorial and User Manual*. University of Illinois at Urbana-Champaign.
- 821 48. Hashash, Y. M. A., C. Phillips, and D. R. Groholski. 2010. "Recent advances in non-linear site response
822 analysis." *Int. Conf. Recent Adv. Geotech. Earthq. Eng. Soil Dyn.*, May 24–29, San Diego, CA.
- 823 49. Hosseini, S. M. M. M., and M. A. Pajouh. 2012. "Comparative study on the equivalent linear and the fully
824 nonlinear site response analysis approaches." *Arab. J. Geosci.* 5: 587–597. [http://dx.doi.org/10.1007/s12517-](http://dx.doi.org/10.1007/s12517-010-0228-9)
825 [010-0228-9](http://dx.doi.org/10.1007/s12517-010-0228-9).
- 826 50. IBC. 2000. *International Building Code-2000*, 5th ed. International Code Council, Inc., Falls Church, VA.
- 827 51. IBC. 2006. *International Building Code 2006*. International Code Council, Inc., Falls Church, VA.
- 828 52. Idriss, I. M. 2008. "An NGA empirical model for estimating the horizontal spectral values generated by
829 shallow crustal earthquakes." *Earthq. Spectra* 24 (1): 217–242. <https://doi.org/10.1193/070613eqs195m>.
- 830 53. Idriss, I. M. 1990. "Response of soft soil sites during earthquakes." *Proc. Int. Conf. Recent Adv. Geotech.*
831 *Earthq. Eng. Soil Dyn.*, St. Louis, MO, 2265–2272.
- 832 54. Imam, A., K. K. Sharma, and V. Kumar. 2023. "Seismic site characterization using multichannel analysis of
833 surface waves in the Singhbhum region of Jharkhand, India: A case study." *Acta Geod. Geoph.* 58: 217–239.
834 <https://doi.org/10.1007/s40328-023-00408-9>.
- 835 55. IS 1893 (Part 1). 2002. *Indian Standard Criteria for Earthquake Resistant Design of Structures – Part 1:*
836 *General Provisions and Buildings*. Bureau of Indian Standards, New Delhi.

- 837 56. IS 1893 (Part 1). 2016. Criteria for Earthquake Resistant Design of Structures – Part 1: General Provisions
838 and Buildings (Sixth Revision). Bureau of Indian Standards, New Delhi.
- 839 57. IS 1893:1962. Indian Standard Recommendations for Earthquake Resistant Design of Structures. Bureau of
840 Indian Standards, New Delhi.
- 841 58. IS 1893:1966. Indian Standard Criteria for Earthquake Resistant Design of Structures. Bureau of Indian
842 Standards, New Delhi.
- 843 59. IS 1893:1970. Indian Standard Criteria for Earthquake Resistant Design of Structures. Bureau of Indian
844 Standards, New Delhi.
- 845 60. IS 2720 (Part 29). 1975. Indian Standard Methods of Test for Soils – Part 29: Determination of Dry Density
846 of Soils In-Place by Core Cutter Method. Bureau of Indian Standards, New Delhi.
- 847 61. Ishibashi, I., and X. Zhang. 1993. “Unified dynamic shear moduli and damping ratios of sand and clay.” *Soils*
848 *Found.* 33 (1): 182–191. <https://doi.org/10.3208/sandf1972.33.182>.
- 849 62. Jishnu, R., S. P. Naik, N. R. Patra, and J. N. Malik. 2013. “Ground response analysis of Kanpur soil along
850 Indo-Gangetic Plains.” *Soil Dyn. Earthq. Eng.* 51: 47–57. <https://doi.org/10.1016/j.soildyn.2013.04.001>.
- 851 63. Joshi, A., and P. Bhardwaj. 2018. “Site characterization using multi-channel analysis of surface waves at
852 locations in Kumaon Himalayas, India.” *J. Indian Geophys. Union* 22 (3): 265–278.
853 <http://dx.doi.org/10.13140/RG.2.2.17867.08487>.
- 854 64. Joyner, W. B., and T. E. Fumal. 1984. “Use of measured shear-wave velocity for predicting geologic site
855 effects on strong ground motion.” In *Proc. 8th World Conf. Earthq. Eng., Vol. 2: 777–783*.
- 856 65. Joyner, W. B., and D. M. Boore. 1981. “Peak horizontal acceleration and velocity from strong motion records
857 including records from the 1979 Imperial Valley, California Earthquake.” *Bull. Seismol. Soc. Am.* 71: 2011–
858 2038. <https://doi.org/10.1785/BSSA0710062011>.
- 859 66. Kabilmany, K., and K. Ishihara. 1990. “Stress dilatancy and hardening laws for rigid granular model of
860 sand.” *Soil Dyn. Earthq. Eng.* 9 (2): 66–77. [https://doi.org/10.1016/S0267-7261\(05\)80020-X](https://doi.org/10.1016/S0267-7261(05)80020-X).
- 861 67. Kalliolglou, P., T. Tika, and K. Pitilakis. 2008. “Shear modulus and damping ratio of cohesive soils.” *J.*
862 *Earthq. Eng.* 12 (6): 879–913. <http://dx.doi.org/10.1080/13632460801888525>.
- 863 68. Kamatchi, P., G. V. Ramana, A. K. Nagpal, and N. Lakshmanan. 2008. “Site-specific analysis of Delhi region
864 for scenario earthquakes.” *Proc. 14th World Conf. Earthq. Eng., Beijing, October 12–17*.
- 865 69. Kanli, A. I., P. Tildy, Z. Pronay, A. Pinar, and L. Hemann. 2006. “Vs30 mapping and soil classification for
866 seismic site effect evaluation in Dinar region, SW Turkey.” *Geophys. J. Int.* 165: 223–235.
867 <https://doi.org/10.1111/j.1365-246X.2006.02882.x>.
- 868 70. Kataria, N. P., M. Shrikhande, and J. D. Das. 2013. “Deterministic seismic hazard analysis of Andaman and
869 Nicobar Islands.” *J. Earthq. Tsunami* 7 (4): 1–19. <http://dx.doi.org/10.1142/S1793431113500358>.
- 870 71. Kayal, J. R. 2008. *Microearthquake seismology and seismotectonics of South Asia*. Springer Science and
871 Business Media. <https://doi.org/10.1007/978-1-4020-8180-4>.
- 872 72. Kayal, J. R. 1987. “Microseismicity and source mechanism study: Shillong Plateau, Northeast India.” *Bull.*
873 *Seismol. Soc. Am.* 77: 184–194. <http://dx.doi.org/10.1785/BSSA0770010184>.

- 874 73. Kayal, J. R. 1998. "Seismicity of Northeast India and surroundings – development over the past 100 years."
875 Mem. Geol. Soc. India, J. Geophys. 19 (1): 9–34.
- 876 74. Kolathayar, S., T. G. Sitharam, and K. S. Vipin. 2012. "Spatial variation of seismicity parameters across
877 India and adjoining areas." Nat. Hazards 60: 1365–1379. <http://dx.doi.org/10.1007/s11069-011-9898-1>.
- 878 75. Kramer, S. L. 1996. Geotechnical Earthquake Engineering. Pearson Education, Delhi. Reprinted 2003.
- 879 76. Kumar, A., P. Anbazhagan, and T. G. Sitharam. 2010. "Shear wave velocity profiling for Lucknow urban
880 centre using seismic refraction survey." Proc. Indian Geotech. Conf., GEOTrendz, 167–170.
- 881 77. Kumar, A., R. Satyanarayana, and B. G. Rajesh. 2022. "Correlation between SPT-N and shear wave velocity
882 (Vs) and seismic site classification for Amaravati city, India." J. Appl. Geophys. 205: 104757.
883 <https://doi.org/10.1016/j.jappgeo.2022.104757>.
- 884 78. Kumar, N., I. A. Parvez, and H. S. Virk. 2005. "Estimation of coda waves attenuation for NW Himalayan
885 region using local earthquakes." Phys. Earth Planet. Inter. 3: 243–258.
886 <http://dx.doi.org/10.1016/j.pepi.2005.03.010>.
- 887 79. Kumar, S. S., and A. M. Krishna. 2013. "Seismic ground response analysis of some typical sites of Guwahati
888 City." Int. J. Geotech. Earthq. Eng. 4 (1): 83–101. <http://dx.doi.org/10.4018/jgee.2013010106>.
- 889 80. Kumar, S. S., A. M. Krishna, and A. Dey. 2014. "Nonlinear site-specific ground response analysis: Case
890 study of Amingaon, Guwahati." 15th Symp. Earthq. Eng., IIT Roorkee, 308–318.
- 891 81. Kumari, K., P. Kumar, and S. S. Kumar. 2024. "Nonlinear seismic ground response analysis for site classes
892 D and E of Bihar Region, India." Indian Geotech. J. 54 (2): 358–393. <http://dx.doi.org/10.1007/s40098-023-00775-8>.
- 893 82. Kwok, A. O. L., J. P. Stewart, and Y. M. A. Hashash. 2008. "Nonlinear ground response analysis of Turkey
894 flat shallow stiff-soil site to strong ground motion." Bull. Seismol. Soc. Am. 98 (1): 331–343.
895 <http://dx.doi.org/10.1785/0120070009>.
- 896 83. Li, X. S., Z. L. Wang, and C. K. Shen. 1992. SUMDES: A nonlinear procedure for response analysis of
897 horizontally layered sites subjected to multi-directional earthquake loading. Dept. of Civil Eng., Univ. of
898 California, Davis.
- 900 84. Liam Finn, W. D., G. R. Martin, and M. K. W. Lee. 1978. "Comparison of dynamic analysis of saturated
901 sand." Proc. ASCE Geotech. Eng. Div. Spec. Conf., Pasadena, CA, 472–491.
- 902 85. Mahajan, A. K. 2009. "NEHRP soil classification and estimation of 1-D site effect of Dehradun fan deposits
903 using shear wave velocity." Eng. Geol. 104 (3–4): 232–240. <https://doi.org/10.1016/j.enggeo.2008.10.013>.
- 904 86. Mahajan, A. K., S. Slob, R. Ranjan, R. Sporry, P. K. Champati Ray, and C. J. Westen. 2007. "Seismic
905 microzonation of Dehradun city using geophysical and geotechnical characteristics in the upper 30 m of soil
906 column." J. Seismol. 11 (4): 355–370. <http://dx.doi.org/10.1007/s10950-007-9055-1>.
- 907 87. Mahajan, A. K., V. C. Thakur, M. L. Sharma, and M. Chauhan. 2010. "Probabilistic seismic hazard map of
908 NW Himalaya and its adjoining area, India." Nat. Hazards 53 (3): 443–457.
909 <http://dx.doi.org/10.1007/s11069-009-9439-3>.

- 910 88. Maheshwari, R. U., A. Boominathan, and G. R. Dodagoudar. 2010. "Seismic site classification and site period
911 mapping of Chennai City using geophysical and geotechnical data." *J. Appl. Geophys.* 72 (3): 52–168.
912 <https://doi.org/10.1016/j.jappgeo.2010.08.002>.
- 913 89. Maiti, S. K., S. K. Nath, M. D. Adhikari, N. Srivastava, P. Sengupta, and A. K. Gupta. 2017. "Probabilistic
914 seismic hazard model of West Bengal, India." *J. Earthq. Eng.* 21 (7): 1113–1157.
915 <http://dx.doi.org/10.1080/13632469.2016.1210054>.
- 916 90. Mandal, H. S., P. K. Khan, and A. K. Shukla. 2014. "Soil responses near Delhi ridge and adjacent regions in
917 greater Delhi during incidence of a local earthquake." *Nat. Hazards* 70: 93–118.
918 <https://doi.org/10.1007/s11069-012-0098-4>.
- 919 91. Matasović, N., and G. A. Ordóñez. 2007. D-MOD2000: A computer program package for seismic response
920 analysis for horizontally layered soil deposits, earthfill dams, solid waste landfills. GeoMotions, LLC.
- 921 92. Matasović, N., and M. Vucetic. 1993. "Cyclic characterization of liquefiable sands." *J. Geotech. Eng.* 119
922 (11): 1805–1822. [http://dx.doi.org/10.1061/\(ASCE\)0733-9410\(1993\)119:11\(1805\)](http://dx.doi.org/10.1061/(ASCE)0733-9410(1993)119:11(1805)).
- 923 93. Mazzoni, S., F. McKenna, M. H. Scott, and G. L. Fenves. 2006. Open system for earthquake engineering
924 simulation (OpenSees): Command language manual. Pacific Earthquake Engineering Center, University of
925 California, Berkeley.
- 926 94. McGuire, R. K. 1976. FORTRAN computer program for seismic risk analysis. Open File Report No. 76-67,
927 US Geological Survey. <https://doi.org/10.3133/ofr7667>.
- 928 95. McGuire, R. K. 1978. FRISK: Computer program for seismic risk analysis using faults as earthquake sources.
929 Open File Report No. 78-1007, US Geological Survey. <https://doi.org/10.3133/ofr781007>.
- 930 96. McGuire, R. K. 2001a. "Deterministic vs. probabilistic earthquake hazards and risks." *Soil Dyn. Earthq. Eng.*
931 21 (5): 377–384. [http://dx.doi.org/10.1016/S0267-7261\(01\)00019-7](http://dx.doi.org/10.1016/S0267-7261(01)00019-7).
- 932 97. McGuire, R. K. 2001b. FRISK-88M: User's manual (version 1.80). Risk Engineering Inc., Boulder, CO.
- 933 98. Menq, F. Y. 2003. Dynamic properties of sandy and gravelly soils. Ph.D. diss., Dept. of Civil Engineering,
934 University of Texas, Austin. <http://hdl.handle.net/2152/779>.
- 935 99. Mhaske, S. Y., and D. Choudhury. 2011. "Geospatial contour mapping of shear wave velocity for Mumbai
936 city." *Nat. Hazards* 59: 317–327. <https://doi.org/10.1007/s11069-011-9758-z>.
- 937 100. Mihalić, S., M. Oštrić, and M. Krkač. 2011. "Seismic microzonation: A review of principles and practice."
938 *Geofizika* 28 (1): 5–20.
- 939 101. Mitra, S., K. Priestley, A. K. Bhattacharyya, and V. K. Gaur. 2005. "Crustal structure and earthquake focal
940 depths beneath northeastern India and South Tibet." *Geophys. J. Int.* 160: 227–248.
941 <https://doi.org/10.1111/j.1365-246X.2004.02470.x>.
- 942 102. Momen, H., and J. Ghaboussi. 1982. "Stress dilatancy and normalized work for sands." *Proc. IUTAM Conf.*
943 *Deformation Failure Granular Mater.*, 10.
- 944 103. Mroz, Z. 1967. "On the description of anisotropic work hardening." *J. Mech. Phys. Solids* 15 (3): 163–175.
945 [https://doi.org/10.1016/0022-5096\(67\)90030-0](https://doi.org/10.1016/0022-5096(67)90030-0).

- 946 104. Mukhopadhyay, M. 1992. "On earthquake focal mechanism studies for the Burmese arc." *Curr. Sci.* 72 (1):
947 72–88.
- 948 105. Mukhopadhyay, M., and S. Dasgupta. 1988. "Deep structure and tectonics of the Burmese arc: Constraints
949 from earthquakes and gravity data." *Tectonophysics* 149: 299–322. [https://doi.org/10.1016/0040-
950 1951\(88\)90180-1](https://doi.org/10.1016/0040-1951(88)90180-1).
- 951 106. Nagamani, D., K. Sivaram, N. P. Rao, and H. V. S. Satyanarayana. 2020. "Ambient noise and earthquake
952 HVSR modeling for site characterization in southern mainland, Gujarat." *J. Earth Syst. Sci.* 129: 1–14.
953 <https://doi.org/10.1007/s12040-020-01443-8>.
- 954 107. Naik, N., and D. Choudhury. 2015. "Deterministic seismic hazard analysis considering different seismicity
955 levels for the state of Goa, India." *Nat. Hazards* 75 (1): 557–580. [http://dx.doi.org/10.1007/s11069-014-1346-
956 6](http://dx.doi.org/10.1007/s11069-014-1346-6).
- 957 108. Naik, N. P., and D. Choudhury. 2013. "Site-specific ground response analysis for typical sites in Panjim city,
958 Goa." *Proc. Indian Geotech. Conf. (IGC-2013)*, Kakinada, India.
- 959 109. Nampally, S., S. Padhy, S. Trupti, P. P. Prasad, and T. Seshunarayana. 2018. "Evaluation of site effects on
960 ground motions based on equivalent linear site response analysis and liquefaction potential in Chennai, South
961 India." *J. Seismol.* 22 (4): 1075–1093. <https://link.springer.com/article/10.1007/s10950-018-9751-z>.
- 962 110. Nandy, D. R. 2001. *Geodynamics of Northeastern India and the adjoining region*. ABC Publications,
963 Calcutta, 209 p.
- 964 111. Nath, S. K., A. Raj, K. K. S. Thingbaijam, and A. Kumar. 2009. "Ground motion synthesis and seismic
965 scenario in Guwahati city—a stochastic approach." *Seismol. Res. Lett.* 80: 233–242.
966 <http://dx.doi.org/10.1785/gssrl.80.2.233>.
- 967 112. Nath, S. K., K. K. S. Thingbaijam, and A. Raj. 2008. "Earthquake hazard in Northeast India—a seismic
968 microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city." *J. Earth Syst.
969 Sci.* 117: 809–831. <http://dx.doi.org/10.1007/s12040-008-0070-6>.
- 970 113. Nath, S. K., M. Vyas, I. Pal, and P. Sengupta. 2005. "A seismic hazard scenario in the Sikkim Himalaya from
971 seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong
972 motion seismometry." *J. Geophys. Res. Solid Earth* 110 (B1). <http://dx.doi.org/10.1029/2004JB003199>.
- 973 114. NDMA. 2010. *Development of probabilistic seismic hazard map of India*. Technical Report, National
974 Disaster Management Authority, Government of India, New Delhi.
- 975 115. NEHRP BSSC. 2000. *NEHRP recommended provisions for seismic regulations for new buildings and other
976 structures, Part 1: Provisions*. FEMA 368. Building Seismic Safety Council, FEMA, Washington, D.C., USA.
- 977 116. NEHRP BSSC. 2003. *NEHRP recommended provisions for the development of seismic regulations for new
978 buildings, Parts 1 and 2*. FEMA 450. FEMA, Washington, D.C., USA.
- 979 117. NEHRP BSSC. 2020. *NEHRP recommended provisions for seismic regulations for new buildings and other
980 structures – Part I: Provisions and Part II: Commentary*. FEMA P-2082-1. FEMA, National Institute of
981 Building Sciences, Washington, D.C.

- 982 118.Okur, D. V., and A. Ansal. 2007. "Stiffness degradation of natural fine-grained soils during cyclic loading."
983 Soil Dyn. Earthq. Eng. 27 (9): 843–854. <https://doi.org/10.1016/j.soildyn.2007.01.005>.
- 984 119.Oldham, R. D. 1899. Report on the Great Earthquake of 12th June, 1897. Mem. Geol. Surv. India 29: 379.
- 985 120.Oldham, T. 1883. "A catalogue of Indian earthquakes from the earliest time to the end of A.D. 1869." Mem.
986 Geol. Surv. India 29: 163–215.
- 987 121.Ordaz, M., and M. A. Salgado-Gálvez. 2017. R-CRISIS validation and verification document. Technical
988 Report, Mexico City, Mexico.
- 989 122.Pagani, M., D. Monelli, G. Weatherill, L. Danciu, H. Crowley, V. Silva, P. Henshaw, et al. 2014.
990 "OpenQuake Engine: An open hazard (and risk) software for the global earthquake model." Seismol. Res.
991 Lett. 85 (3): 692–702. <http://dx.doi.org/10.1785/0220130087>.
- 992 123.Pallav, K., S. T. G. Raghukanth, and K. D. Singh. 2010. "Surface level ground motion estimation for 1869
993 Cachar earthquake (Mw 7.5) at Imphal city." J. Geophys. Eng. 7 (3): 321–331.
994 <http://dx.doi.org/10.1088/1742-2132/7/3/010>.
- 995 124.Pandey, B., R. S. Jakka, and A. Kumar. 2016. "Influence of local site conditions on strong ground motion
996 characteristics at Tarai region of Uttarakhand, India." Nat. Hazards 81 (2): 1073–1089.
997 <https://link.springer.com/article/10.1007/s11069-015-2120-0>.
- 998 125.Parhi, P. S., U. Balunaini, S. M. Sravanam, and V. K. Mauriya. 2020. "Site characterization of existing and
999 abandoned coal ash ponds using shear-wave velocity from multichannel analysis of surface waves." J.
1000 Geotech. Geoenviron. Eng. 146 (11): 04020115. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0002366](https://doi.org/10.1061/(ASCE)GT.1943-5606.0002366).
- 1001 126.Park, C. B., R. D. Miller, and J. Xia. 1998. "Imaging dispersion curves of surface waves on multi-channel
1002 record." Proc. 68th Annu. Int. Mtg. Soc. Explor. Geophys., 1377–1380. <https://doi.org/10.1190/1.1820161>.
- 1003 127.Park, C. B., R. D. Miller, and J. Xia. 1999. "Multi-channel analysis of surface waves." Geophysics 64 (3):
1004 800–808. <http://dx.doi.org/10.1190/1.1444590>.
- 1005 128.Parvez, I. A., F. Vaccari, and G. F. Panza. 2003. "A deterministic seismic hazard map of India and adjacent
1006 areas." Geophys. J. Int. 155: 489–508. <http://dx.doi.org/10.1046/j.1365-246X.2003.02052.x>.
- 1007 129.Patil, N. S., J. Das, A. Kumar, M. M. Rout, and R. Das. 2014. "Probabilistic seismic hazard assessment of
1008 Himachal Pradesh and adjoining regions." J. Earth Syst. Sci. 123 (1): 49–62.
1009 <http://dx.doi.org/10.1007/s12040-013-0378-8>.
- 1010 130.Phanikanth, V. S., D. Choudhury, and G. R. Reddy. 2011. "Equivalent-linear seismic ground response
1011 analysis of some typical sites in Mumbai." Geotech. Geol. Eng. 29 (6): 1109–1126.
1012 <http://dx.doi.org/10.1007/s10706-011-9443-8>.
- 1013 131.Presti, D. L., C. Lai, and S. Foti. 2004. "Geophysical and geotechnical investigations for ground response
1014 analyses." In Recent Advances in Earthquake Geotechnical Engineering and Microzonation, ed. Atilla Ansal,
1015 101–138. https://doi.org/10.1007/1-4020-2528-9_5.
- 1016 132.Puri, N., and A. Jain. 2019. "Microzonation of seismic hazard for the state of Haryana, India." J. Geol. Soc.
1017 India 94: 297–308. <http://dx.doi.org/10.1007/s12594-019-1310-x>.

- 1018 133. Putti, S. P., and N. Satyam. 2018. "Ground response analysis and liquefaction hazard assessment for
1019 Vishakhapatnam city." *Innov. Infrastruct. Solut.* 3 (1): 12. <http://dx.doi.org/10.1007/s41062-017-0113-4>.
- 1020 134. Pyke, R. M. 2000. TESS: A computer program for nonlinear ground response analyses. TAGA Engineering
1021 Systems & Software, Lafayette, CA.
- 1022 135. Raghukanth, S. T. G. 2010. "Estimation of seismicity parameters for India." *Seismol. Res. Lett.* 81: 207–
1023 217. <http://dx.doi.org/10.1785/gssrl.81.2.207>.
- 1024 136. Raghukanth, S. T. G., and S. Nadh Somala. 2009. "Modeling of strong-motion data in northeastern India: Q,
1025 stress drop, and site amplification." *Bull. Seismol. Soc. Am.* 99 (2A): 705–725.
1026 <http://dx.doi.org/10.1785/0120080025>.
- 1027 137. Ramancharla, P. K., and C. V. R. Murty. 2014. "Earthquake safety of houses in India: Understanding the
1028 bottlenecks in implementation." *Indian Concr. J.* 88 (9): 51–63.
- 1029 138. Ramberg, W., and W. R. Osgood. 1943. Description of stress-strain curves by three parameters. Report No.
1030 NACA-TN-902, National Advisory Committee for Aeronautics, Washington, DC.
- 1031 139. Rao, K. S., and G. W. Rathod. 2014. "Seismic microzonation of Indian megacities: A case study of NCR
1032 Delhi." *Indian Geotech. J.* 44 (2): 132–148. <http://dx.doi.org/10.1007/s40098-013-0084-0>.
- 1033 140. Rao, K. S., and D. N. Satyam. 2004. "Site characterization through microtremor studies for seismic
1034 microzonation of Delhi region." *Proc. 6th Int. Conf. Soil Mech. Geotech. Eng., Osaka*: 2703–2706.
1035 <http://dx.doi.org/10.3233/978-1-61499-656-9-2703>.
- 1036 141. Rao, K. S., T. P. Thakker, A. Aggarwal, T. Bhandari, and S. Kabra. 2012. "Deterministic seismic hazard
1037 analysis of Ahmedabad region, Gujarat." *Int. J. Earth Sci. Eng.* 5 (2): 206–213.
- 1038 142. Rao, N. P., M. R. Kumar, T. Seshunarayana, A. K. Shukla, G. Suresh, Y. Pandey, and H. Gupta. 2011. "Site
1039 amplification studies towards seismic microzonation in Jabalpur urban area, central India." *Phys. Chem.*
1040 *Earth* 36 (16): 1247–1258. <https://doi.org/10.1016/j.pce.2011.01.002>.
- 1041 143. Rayhani, M. H. T., El Naggar, M. H., Tabatabaei, S. H. 2008. "Nonlinear analysis of local site effects on
1042 seismic ground response in the Bam earthquake." *Geotechnical and Geological Engineering* 26 (1): 91–100.
1043 <http://dx.doi.org/10.1007/s10706-007-9149-0>.
- 1044 144. Reasenber, P. 1985. "Second-order moment of central California seismicity, 1969–1982." *Journal of*
1045 *Geophysical Research* 90: 5479–5496.
- 1046 145. Reddy, M. M., Rao, C. H., Reddy, K. R., Kumar, G. K. 2021. "Seismic site classification and ground response
1047 analysis of Amaravati region, Andhra Pradesh, India." *Disaster Advances* 14 (3): 10–20.
- 1048 146. Rollins, K. M., Evans, M. D., Diehl, N. B., III, W. D. D. 1998. "Shear modulus and damping relationships
1049 for gravels." *Journal of Geotechnical and Geoenvironmental Engineering* 124 (5): 396–405.
1050 [https://doi.org/10.1061/\(ASCE\)1090-0241\(1998\)124:5\(396\)](https://doi.org/10.1061/(ASCE)1090-0241(1998)124:5(396)).
- 1051 147. Roten, D., Fäh, D., Bonilla, L. F., Alvarez-Rubio, S., Weber, T. M., Laue, J. 2009. "Estimation of non-linear
1052 site response in a deep Alpine valley." *Geophysical Journal International* 178 (3): 1597–1613.
1053 <https://doi.org/10.1111/j.1365-246X.2009.04246.x>.

- 1054 148.Saha, A., Saha, K., Dey, A. K. 2021. "Seismic site classification and site period determination of NIT Silchar
1055 using MASW." In *Geohazards: Proceedings of IGC 2018*, Springer Singapore, 507–522.
1056 https://doi.org/10.1007/978-981-15-6233-4_36.
- 1057 149.Sairam, B., Singh, A. P., Patel, V., Pancholi, V., Chopra, S., Dwivedi, V. K., Kumar, M. R. 2018. "Influence
1058 of local site effects in the Ahmedabad megacity on the damage due to past earthquakes in northwestern
1059 India." *Bulletin of the Seismological Society of America* 108 (4): 2170–2182.
1060 <https://doi.org/10.1785/0120170266>.
- 1061 150.Satyam, D. N., Rao, K. S. 2008. "Seismic site characterization in Delhi region using multi-channel analysis
1062 of shear wave velocity (MASW) testing." *Electronic Journal of Geotechnical Engineering* 13: 167–183.
- 1063 151.Satyam, N. D., Towhata, I. 2016. "Site-specific ground response analysis and liquefaction assessment of
1064 Vijayawada city (India)." *Natural Hazards* 81 (2): 705–724. <https://doi.org/10.1007/s11069-016-2166-7>.
- 1065 152.Schnabel, P. B., Lysmer, J., Seed, H. B. 1972. SHAKE: A computer program for earthquake response analysis
1066 of horizontally layered sites. Report No. EERC72-12, University of California, Berkeley.
- 1067 153.Scordilis, E. M. 2006. "Empirical global relations converting Ms and Mb to moment magnitude." *Journal of*
1068 *Seismology* 10: 225–236. <https://doi.org/10.1007/s10950-006-9012-4>.
- 1069 154.Seed, H. B., Idriss, I. M. 1970. Soil moduli and damping factors for dynamic response analyses. Report No.
1070 EERC-70-10, University of California, Berkeley.
- 1071 155.Seed, H. B., Ugas, C., Lysmer, J. 1976. "Site-dependent spectra for earthquake-resistant design." *Bulletin of*
1072 *the Seismological Society of America* 66: 221–243. <https://doi.org/10.1785/BSSA0660010221>.
- 1073 156.Seed, H. B., Wong, R. T., Idriss, I. M., Tokimastu, K. 1986. "Moduli and damping factors for dynamic
1074 analysis of cohesionless soils." *Journal of Geotechnical Engineering* 112 (11): 1016–1032.
- 1075 157.Shiuly, A., Narayan, J. P. 2012. "Deterministic seismic microzonation of Kolkata city." *Natural Hazards* 60:
1076 223–240. <http://dx.doi.org/10.1007/s11069-011-0004-5>.
- 1077 158.Shukla, J., Choudhury, D. 2012a. "Estimation of seismic ground motions using deterministic approach for
1078 major cities of Gujarat." *Natural Hazards and Earth System Sciences* 12: 2019–2037.
1079 <http://dx.doi.org/10.5194/nhess-12-2019-2012>.
- 1080 159.Shukla, J., Choudhury, D. 2012b. "Seismic hazard and site-specific ground motion for typical ports of
1081 Gujarat." *Natural Hazards* 60 (2): 541–565. <https://doi.org/10.1007/s11069-011-0042-z>.
- 1082 160.Sil, A., Sitharam, T. G. 2014. "Dynamic site characterization and correlation of shear wave velocity with
1083 standard penetration test 'N' values for the city of Agartala, Tripura State, India." *Pure and Applied*
1084 *Geophysics* 171: 1615–1631. <http://dx.doi.org/10.1007/s00024-013-0754-y>.
- 1085 161.Sil, A., Sitharam, T. G. 2016. "Site-specific design response spectrum proposed for the capital city of
1086 Agartala, Tripura." *Geomatics, Natural Hazards and Risk* 7 (5): 1610–1630.
1087 <http://dx.doi.org/10.1080/19475705.2015.1124929>.
- 1088 162.Singh, A. P., Parmar, A., Chopra, S. 2017. "Microtremor study for evaluating the site response characteristics
1089 in the Surat City of western India." *Natural Hazards* 89 (3): 1145–1166.
1090 <https://link.springer.com/article/10.1007/s11069-017-3012-2>.

- 1091 163.Singh, M., Duggal, S. K., Singh, V. P. 2021. “A study to establish regression correlation between shear wave
1092 velocity and N-Value for Varanasi City, India.” Proceedings of the National Academy of Sciences, India
1093 Section A: Physical Sciences 91: 405–417. <https://doi.org/10.1007/s40010-020-00686-w>.
- 1094 164.Sitharam, T. G., Govindaraju, L. 2004. “Geotechnical aspects and ground response studies in Bhuj
1095 earthquake, India.” Geotechnical and Geological Engineering 22: 439–455.
1096 <http://dx.doi.org/10.1023/B:GEGE.0000025045.90576.d3>.
- 1097 165.Sitharam, T. G., Sil, A. 2014. “Comprehensive seismic hazard assessment of Tripura and Mizoram states.”
1098 Journal of Earth System Science 123 (4): 837–857. <http://dx.doi.org/10.1007/s12040-014-0438-8>.
- 1099 166.Socco, L. V., Strobbia, C. 2004. “Surface-wave method for near-surface characterization: A tutorial.” Near
1100 Surface Geophysics 2 (4): 165–185. <http://dx.doi.org/10.3997/1873-0604.2004015>.
- 1101 167.Stepp, J. C. 1972. “Analysis of the completeness of the earthquake sample in the Puget Sound area and its
1102 effects on statistical estimates of earthquake hazard.” Proceedings of International Conference on
1103 Microzonation for Safer Construction Research and Application, Seattle, Washington.
- 1104 168.Stewart, J. P., Kwok, A. O. L. 2008. “Nonlinear seismic ground response analysis: Code usage protocols and
1105 verification against vertical array data.” Proceedings of International Conference on Recent Advances in
1106 Geotechnical Earthquake Engineering and Soil Dynamics IV, Sacramento, California.
- 1107 169.Stokoe II, K. H., Rix, G. J., Nazarian, S. 1989. “In situ seismic testing with surface waves: Processing.” XII
1108 International Conference on Soil Mechanics and Foundation Engineering, 331–334.
- 1109 170.Sun, J. I., Golesorkhi, R., Seed, H. B. 1988. Dynamic moduli and damping ratios for cohesive soils.
1110 Earthquake Engineering Research Center Report No. UCB/EERC 88/15, University of California, Berkeley.
- 1111 171.Taipodia, J., Baglari, D., Dey, A. 2017. “Resolution of dispersion image obtained from active MASW
1112 survey.” Disaster Advances 10 (11): 34–45.
- 1113 172.Taipodia, J., Baglari, D., Dey, A. 2018. “Recommendations for generating dispersion images of optimal
1114 resolution from active MASW survey.” Innovative Infrastructure Solutions 3: 1–19.
1115 <https://doi.org/10.1007/s41062-017-0120-5>.
- 1116 173.Taipodia, J., Baglari, D., Dey, A. 2019. “Effect of source characteristics on the resolution of dispersion image
1117 from active MASW survey.” Indian Geotechnical Journal 49: 314–327. <https://doi.org/10.1007/s40098-018-0335-1>.
- 1118
- 1119 174.Taipodia, J., Dey, A. 2017a. “Impact of frequency filtering and temporal muting on the resolution of
1120 dispersion image.” 13th International Conference on Vibration Problems (13ICOVP), Guwahati, India: 1–
1121 11.
- 1122 175.Taipodia, J., Dey, A. 2017b. “Impact of offset on the resolution of dispersion image in active MASW survey.”
1123 Geotechnics for Natural and Engineered Sustainable Technologies: Indian Geotechnical Conference
1124 (GeoNEst: IGC-2017), Guwahati, India: 1–4.
- 1125 176.Taipodia, J., Dey, A. 2018. “Impact of data preprocessing parameters on the accuracy of the inverted Vs
1126 profile in MASW.” International Conference on Advances in Concrete, Structural & Geotechnical
1127 Engineering (ACSGE - 2018), BITS Pilani, India: 1–6.

- 1128 177. Taipodia, J., Dey, A., Gaj, S., Baglari, D. 2020. "Quantification of the resolution of dispersion image in active
1129 MASW survey and automated extraction of dispersion curve." *Computers & Geosciences* 135: 104360.
1130 <https://doi.org/10.1016/j.cageo.2019.104360>.
- 1131 178. Tandon, A. N. 1992. "Seismology in India: an overview up to 1970." *Current Science* 62 (1–2): 9–16.
- 1132 179. Tandon, A. N., Srivastava, H. N. 1975. "Focal mechanism of some recent Himalayan earthquakes and
1133 regional plate tectonics." *Bulletin of the Seismological Society of America* 65: 963–969.
1134 <http://dx.doi.org/10.1785/BSSA0650040963>.
- 1135 180. TC4-ISSMGE. 1999. *Manual for Zonation on Seismic Geotechnical Hazard, Revised Edition*. International
1136 Society of Soil Mechanics and Geotechnical Engineering (ISSMGE).
- 1137 181. Tewari, R. P. 2000. "Earthquake hazards and mitigation in India with special reference to northeastern India."
1138 *ENVIS Bulletin Himalayan Ecology* 8 (2): 15–22.
- 1139 182. Thaker, T. P., Rao, K. S., Gupta, K. K. 2010. "Site-specific ground response studies for coastal soil, Kutch,
1140 Gujarat: A case study." *International Journal of Earth Sciences and Engineering* 3 (4): 543–553.
- 1141 183. Thaker, T. P., Rathod, G. W., Rao, K. S., Gupta, K. K. 2012. "Use of seismotectonic information for the
1142 seismic hazard analysis for Surat city, Gujarat, India: Deterministic and probabilistic approach." *Pure and
1143 Applied Geophysics* 169: 37–54. <http://dx.doi.org/10.1007/s00024-011-0317-z>.
- 1144 184. Thokchom, S., Rastogi, B. K., Dogra, N. N., Pancholi, V., Sairam, B., Bhattacharya, F., Patel, V. 2017.
1145 "Empirical correlation of SPT blow counts versus shear wave velocity for different types of soils in Dholera,
1146 Western India." *Natural Hazards* 86: 1291–1306. [https://link.springer.com/article/10.1007/s11069-017-
1147 2744-3](https://link.springer.com/article/10.1007/s11069-017-2744-3).
- 1148 185. Tinti, S., Mulargia, F. 1985. "Completeness analysis of a seismic catalog." *Annales Geophysicae* 3 (3): 407–
1149 414.
- 1150 186. Uma Maheshwari, R., Boominathan, A., Dodagoudar, G. R. 2010. "Effective stress versus total stress ground
1151 response analyses for a typical site in Chennai (India)." *Proceedings of the 5th International Conference on
1152 Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Paper No. 3.18b, May 24–
1153 29, San Diego, California*.
- 1154 187. Vipin, K. S., Anbazhagan, P., Sitharam, T. G. 2009. "Estimation of peak ground acceleration and spectral
1155 acceleration for south India with local site effects: Probabilistic approach." *Natural Hazards and Earth System
1156 Sciences* 9: 865–878. <http://dx.doi.org/10.5194/nhess-9-865-2009>.
- 1157 188. Vucetic, M., Dobry, R. 1991. "Effect of soil plasticity on cyclic response." *Journal of Geotechnical
1158 Engineering* 117 (1): 89–107.
- 1159 189. Walling, M. Y., Mohanty, W. K. 2009. "An overview on the seismic zonation and microzonation studies in
1160 India." *Earth-Science Reviews* 96 (1–2): 67–91. <http://dx.doi.org/10.1016/j.earscirev.2009.05.002>.
- 1161 190. Xia, J., Chen, C., Li, P. H., Lewis, M. J. 2004. "Delineation of a collapse feature in a noisy environment
1162 using a multichannel surface wave technique." *Geotechnique* 54: 17–27.
1163 <http://dx.doi.org/10.1680/geot.2004.54.1.17>.

- 1164 191.Xia, J., Miller, R. D., Park, C. B. 1999. "Estimation of near-surface shear-wave velocity by inversion of
1165 Rayleigh wave." *Geophysics* 64 (3): 691–700. <http://dx.doi.org/10.1190/1.1444578>.
- 1166 192.Zhang, J., Andrus, R., Juang, C. H. 2005. "Normalized shear modulus and material damping ratio
1167 relationships." *Journal of Geotechnical and Geoenvironmental Engineering* 131 (4): 453–464.
1168 [http://dx.doi.org/10.1061/\(ASCE\)1090-0241\(2005\)131:4\(453\)](http://dx.doi.org/10.1061/(ASCE)1090-0241(2005)131:4(453)).
- 1169 193.Zhang, J., Andrus, R., Juang, C. H. 2008. "Model uncertainty in normalized shear modulus and damping
1170 ratio relationships." *Journal of Geotechnical and Geoenvironmental Engineering* 134 (1): 24–36.
1171 [http://dx.doi.org/10.1061/\(ASCE\)1090-0241\(2008\)134:1\(24\)](http://dx.doi.org/10.1061/(ASCE)1090-0241(2008)134:1(24)).
- 1172 194.Zheng, W., Luna, R. 2011. "Nonlinear site response and liquefaction analysis in the New Madrid seismic
1173 zone." *Geotechnical and Geological Engineering* 29: 463–475. <https://doi.org/10.1007/s10706-011-9396-y>.