

# Seismic Hazard and Risk Assessment in Maharashtra: A Critical Review



Abdullah Ansari , K. S. Rao, and A. K. Jain

**Abstract** In peninsula India, the state of Maharashtra has suffered from frequent intra-plate earthquakes. In 1967, the Koyna earthquake caused few hundred deaths and structural damage, and then, in 1993, the Killari earthquake in Latur district caused thousands of deaths and enormous structural damage. There are two basic methods for assessing the seismic ground motion hazard in a particular region or at a specific site, namely deterministic methods and probabilistic methods. In deterministic seismic hazard analysis, a particular earthquake scenario is presumed. On another hand, uncertainties in earthquake location, size, and time are considered in case of probabilistic seismic hazard analysis. Geotechnical and geophysical data-based site characterization helped to divide the area into smaller zones giving a new direction toward microzonation. This paper deals with the compilation of various studies carried out at different region of the Maharashtra based on several approaches. A critical review is presented on each of these methods, highlighting their limitations and suitability of application.

**Keywords** Seismic hazard · Seismic response · MASW · Liquefaction · Shear wave velocity

## 1 Introduction

Millions of people are affected by natural hazards every year, and their impact can be calamitous. From the destructions of building to the spread of disease, natural hazards can devastate entire countries overnight. Tsunamis, earthquakes, and typhoons do not just wreak havoc on the land; they also disrupt people's lives in both densely populated cities as well as remote villages and rural areas. Increasing effects of natural hazards viz. landslides, tsunami, floods around the world have a direct social, economic, and environmental impact. In the domain of the Indian sub-continent, the ongoing collision between the Indian plate and the Eurasian plate has resulted in

---

A. Ansari (✉) · K. S. Rao · A. K. Jain  
Department of Civil Engineering, Indian Institute of Technology, Delhi, New Delhi 110016, India  
e-mail: [cez188391@iitd.ac.in](mailto:cez188391@iitd.ac.in)

the formation of the Himalayas in the north and a subduction zone in the southwest along the Sumatra-Andaman trench. Indian sub-continent experienced several devastating catastrophic events, viz. the 1993 Latur earthquake (Mw 6.2) and 2001 Bhuj earthquake (Mw 7.6) in Stable Continental Region (SCR) of Western India; 2005 Muzaffarabad earthquake (Mw 7.6) in Kashmir; 2015 Gorkha earthquake (Mw 7.8) along the active plate boundary in Himalaya; and 2004 Sumatra-Andaman earthquake (Mw 9.3) associated with a transoceanic tsunami in the Indian Ocean [1].

In peninsula India, the state of Maharashtra, along with Gujarat and Madhya Pradesh, has suffered from frequent deadly and damaging earthquakes. The western coastal areas of Maharashtra along with the state capital Mumbai and Pune city have both been strongly shaken in the past in 1618 and 1764, respectively, [2]. Seismologists identified several faults in this region out of which many show evidence of movement during the Holocene epoch. The major Chiplin fault lies along the Sahyadri range running from the mouth of Bombay Harbor to the Sangammeshwar area in Ratnagiri district. While the west coast fault runs along the eastern shore of the Thane Creek in the Mumbai area, along the flanks of the Parsik Hills. The Vidharbha region is intersected by Kadam fault which runs from Bhusawal city into northern Andhra Pradesh. The 1967 Koyna earthquake (Mw 6.6) is the largest known case of Reservoir Induced Seismicity (RIS) in the world. The devastating Latur earthquake (Mw 6.2) of 1993 in southern part of the state has claimed an estimated 11,000 human lives [3].

To study these seismic events, various methods and techniques are used. Deterministic- and probabilistic-based seismic hazard analysis of the earthquake prone source-site area carried out to know about the peak ground acceleration and return interval of the earthquakes in a particular area or site. Geotechnical and geophysical data-based site characterization and ground response analysis help to divide the area into smaller zones giving a new direction toward microzonation. Liquefaction occurs generally due to rapid loading during seismic events, where there is not sufficient time for dissipation of excess pore-water pressures through natural drainage. Liquefaction Potential Index (LPI) is evaluated at each borehole location from the obtained Factors of Safety (FS) to predict the potential of liquefaction to cause damage at the surface level at the site of interest. This paper deals with the compilation of various studies carried out at different region of the Maharashtra based on several approaches. A critical review is presented on each of these methods, highlighting their limitations and suitability of application.

## 2 Earthquakes in Maharashtra

After 2001 Bhuj earthquake in Gujarat, seismic hazard map of India was updated by the Bureau of Indian Standards (BIS). The latest seismic zonation map of India includes the Beed, Osmanabad, and Latur, along with eastern sections of Ahmednagar, Pune, Satara, and Sangli districts in Zone III. Districts viz. Raigad, Ratnagiri, and Satara lie in Zone IV, where maximum expected intensity of seismic motion is

**Table 1** Major earthquakes in Maharashtra after 1950

Date	Region	Location	Earthquake data	
			Magnitude (Mw)	Depth (km)
April 08 1951	Konkan area	18.500 N, 70.800 E	6.0	13
December 13 1957	Koyna area	17.300 N, 73.700 E	6.1	15
December 11 1967	Koyna area	17.450 N, 73.850 E	6.6	27
September 26 1970	Wai area	18.000 N, 74.000 E	5.5	19
September 14 1983	Bhatsa area	19.640 N, 73.540 E	5.2	33
September 30 1993	Latur area	18.090 N, 76.470 E	6.2	10
March 12 2000	Koyna area	17.244 N, 73.707 E	5.3	9
July 27 2003	Sindvani area	21.878 N, 74.341 E	5.1	20
March 14 2005	Koyna area	17.139 N, 73.687 E	5.1	14
September 16 2008	Koyna area	17.289 N, 73.815 E	5.5	11
December 17 2009	Satara area	17.421 N, 73.810 E	5.1	10
July 12 2015	Satara area	17.212 N, 73.75 E	5.3	6
August 19 2017	Karad area	17.194 N, 73.825 E	5.2	8

VIII. The remaining western and northwestern districts of the state fall in Zone III [4, 5]. India Meteorological Department (IMD) under Government of India responsible for monitoring seismic activity in and around the country helping in collection the real-time earthquake data. Following Table 1 gives the detailed description about the major earthquakes event occurred in the Maharashtra region after 1950.

### 3 Seismic Hazard Assessment

The seismic hazard could be defined as the likelihood of experiencing a specified intensity of any damaging phenomenon at a site or all over a region during a considered period of time. The development of the methodology for analyzing the probability of seismic hazards has originated from the engineering needs for better designs [6]. Seismic hazard assessment is analogous to long-term earthquake prediction [7, 8]. Two basic methodologies used for Seismic Hazard Assessment (SHA) are the Deterministic Seismic Hazard Assessment (DSHA) and the Probabilistic Seismic Hazard Assessment (PSHA) approaches. In the Deterministic Seismic Hazard Assessment (DSHA), the strong ground motion parameters are estimated for the maximum credible earthquake, assumed to occur at the closest possible distance from the site of

interest, without considering the likelihood of its occurrence during a specified exposure period. On the other hand, in PSHA, rather than searching for elusive worst-case ground motion, all possible earthquake events and resulting ground motions along with their associated probabilities of occurrence are considered to estimate the level of ground motion intensity exceeded with some tolerably low rate.

### 3.1 Deterministic Seismic Hazard Analysis (DSHA)

This method of seismic analysis is based on Maximum Credible Earthquake (MCE) and estimates the maximum size of an earthquake located at defined distance from the site. The basic steps involved in the process of deterministic seismic hazard assessment are as follows, as shown in Fig. 1.

- a. **Identification of earthquake sources:** These sources could be either clearly understood and defined faults or less well understood and less well defined geologic structures or seismotectonic provinces of many thousands of square kilometers. Earthquake sources could be either clearly understood and defined faults or less well understood and less well defined any geologic structures or seismotectonic region of many thousands of square kilometers. The individual sources could be configured as points, lines, areas, or volumes [6]. The geometry and potential of each earthquake source need to be defined well before jumping to next step.
- b. **Evaluation of source-to-site distance:** For each source zone, the shortest distance between the source zone and site of interest is selected.

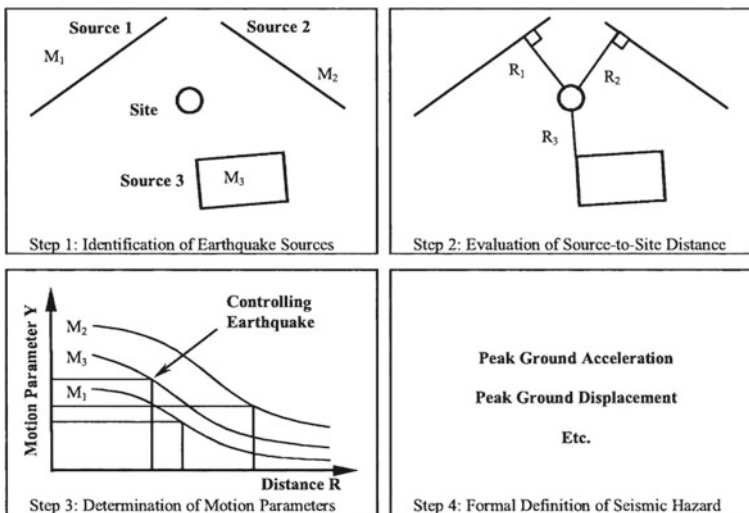


Fig. 1 Steps of deterministic seismic hazard analysis (DSHA) [9]

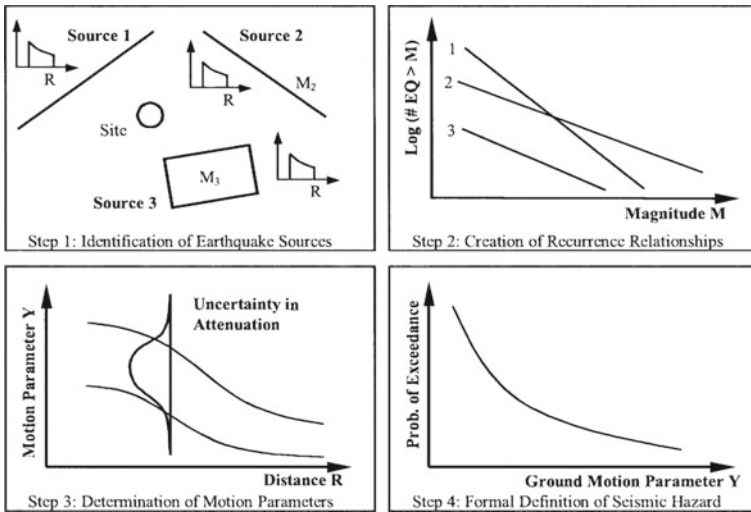


Fig. 2 Steps of probabilistic seismic hazard analysis (PSHA) [11]

- c. **Determination of motion parameters:** The earthquake potential of each source specified in the first step should be defined in terms of a maximum earthquake known as either "maximum credible earthquake" which is the maximum earthquake capable of occurring in an area or on a given fault during the current tectonic regime. They are also defined as "maximum expectable earthquake," or "design earthquake." For regional seismicity, two levels of maximum earthquakes could be considered as in the case of the U.S. Nuclear Regulatory Commission: "Safe shutdown earthquake" and "operating basis earthquake" selected for hazard assessment.
- d. **Formal definition of seismic hazard:** This can be defined as the hazard at the site of interest represented by specific peak ground motion such as response spectrum ordinate values, describing the earthquake effects [10] (Fig. 2).

### 3.2 Probabilistic Seismic Hazard Analysis (PSHA)

Probabilistic seismic hazard analysis is a rational solution to the different types of dilemmas posed by uncertainties. The first methodology applied to most of the probabilistic seismic hazard analyses was defined by [6] in 1968. The four steps involved in this method are explained below:

- a. **Identification of earthquake sources:** The types of the sources may range from small planar faults to large seismotectonic provinces. The source-site distances for each source are calculated considering the spatial uncertainty. The distances from all possible locations to the site within the earthquake source should be

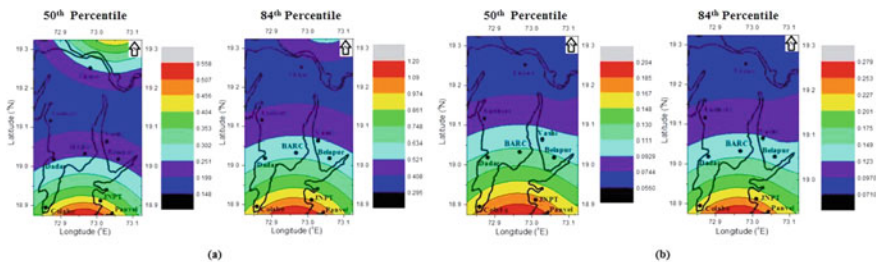
certainly considered since these earthquakes are assumed to happen anywhere within that source.

- b. **Creation of recurrence relationships:** In contrast to the deterministic analyses which try to use one controlling earthquake or one maximum earthquake for each source separately, each source is characterized by an earthquake probability distribution or simply by a recurrence relationship in probabilistic analyses.
- c. **Determination of motion parameters:** A set of earthquake attenuation or ground motion curves relating a ground motion parameter to distance for an earthquake of a given size is required.
- d. **Formal definition of seismic hazard:** The hazard curve which integrates the effects of all the earthquakes of different sizes occurring at different locations within different earthquake sources at different probabilities of occurrence is formed to show the probability of exceeding different levels of ground motion levels at the site during a specified period [10] (Table 2).

The seismic hazard of Greater Mumbai region is evaluated using DSHA methodology [12]. The spatial variation of 50 and 84th percentile of Spectral Acceleration ( $S_a$ ) values shown in Fig. 3 for 0.2 and 1 s period. Seismic hazard for Peak Horizontal Acceleration (PHA) increases steadily from relatively low to high seismicity from the center to southern and northern parts of the Greater Mumbai region. The same hazard pattern is observed for  $S_a$  values at short period (0.2 s); however, for long period (1 s), the hazard is observed to be concentrated on southern part of the region

**Table 2** Advantages and disadvantages of PSHA and DSHA [9]

Advantages	Limitations
<b>Deterministic Seismic Hazard Analysis (DSHA)</b>	
Based on design maximum earthquake	Frequency or probability of earthquakes is not considered
Gives conservative results and high level of safety	Uncertainties involved in the selection of inputs are not considered
	If active faults are not well defined, then the source-to-site distance is difficult to determine
<b>Probabilistic Seismic Hazard Analysis (PSHA)</b>	
The spatial uncertainty, i.e., randomness in earthquake location is explicitly considered	A range of possible ground motion levels, instead of a unique value, is the result
The temporal uncertainty, i.e., probability of occurrence of earthquakes is included	Deaggregation of the results becomes essential due to the multiple contributions of sources, magnitudes, and distances
Uncertainties involved in the process are incorporated through a logic tree	The use of logic tree in PSHA in itself involves use of the subjective judgment
Risk and cost of a project can be easily optimized by selecting an appropriate return period of earthquake	Inclusion of uncertainties introduces more complexities in the analysis



**Fig. 3** Spatial variation of 50th percentile and 84th percentile values for **a** 0.2 s, **b** 1 s at bedrock [12]

with a steady decrease toward north side. The PHA values for Greater Mumbai region ranges between 0.076 and 0.328 g.

### 4 Liquefaction Hazard Assessment

Liquefaction Potential Index (LPI) is a parameter used to represent regional liquefaction potential [13, 14]. LPI at a specific site is computed by integrating the Factors of Safety (FS) along the soil column. A weighting function is added to give more weight to the layers closer to the ground surface. The Liquefaction Potential Index (LPI), proposed by [15, 16] is expressed as follows:

$$LPI = \int_0^{20} F \cdot w(z) dz \tag{1}$$

where  $z$  is depth of the midpoint of the soil layer), and  $dz$  is differential increment of depth. The weighting factor,  $w(z)$ , and the severity factor,  $F(z)$ , are calculated as per the following expressions:

$$\begin{aligned}
 F(z) &= 1 - FS \quad \text{for } FS < 1.0 \\
 F(z) &= 0 \quad \text{for } FS \geq 1.0 \\
 w(z) &= 10 - 0.5z \quad \text{for } z < 20 \text{ m} \\
 w(z) &= 0 \quad \text{for } z > 20 \text{ m}
 \end{aligned}$$

For the soil profiles with the depth less than 20 m, LPI is calculated using the following expression [4],

$$LPI = \sum_{i=1}^n w_i F_i H_i \tag{2}$$

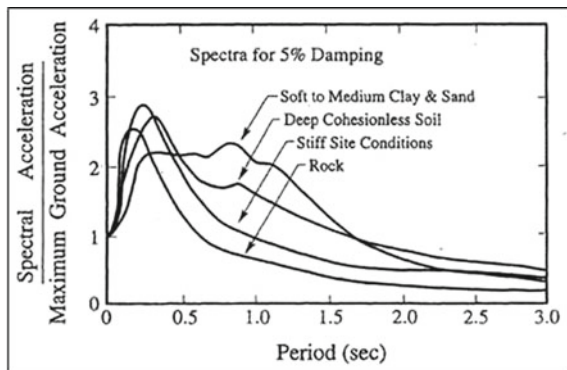
where  $H_i$  is thickness of the discretized soil layers;  $n$  is number of layers;  $F_i$  is liquefaction severity for  $i$ th layer;  $FS_i$  is the factor of safety for  $i$ th layer;  $w_i$  is the weighting factor ( $=10-0.5z_i$ ); and  $z_i$  is the depth of  $i$ th layer (m).

To predict the potential of liquefaction causing damage at the surface level of the site of interest evaluated the Liquefaction Potential Index (LPI) at each borehole location from the obtained Factors of Safety (FS) for Greater Mumbai [17]. LPI contour maps prepared for Mumbai region showed that a high degree of liquefaction damages is likely to occur at many sites in the city during severe seismic event. These LPI contour maps help to check the vulnerability of the area against liquefaction. These contour maps can also be used effectively for seismic safety plans and in the seismic hazard mitigation programs followed by seismic microzonation.

### 5 Seismic Response and Geophysical Investigation

Seismic hazard analysis gives the ground shaking at the bedrock. However, the ground shaking and the associated damage to engineered structures can be strongly influenced by the geology and topography in their vicinities. The influence of local site conditions on the nature of the ground motions and the damage they may cause have been observed and studied [13]. The early work of seismologists studied site amplification shows that they used to assume linear soil behavior, and they rarely considered the soil non-linearity in their assessments of site conditions [7, 18]. On the other hand, the non-linear approach is complicated and cannot model the actual hysteretic stress–strain behavior of cyclically loaded soil. Therefore, the equivalent linear method that modifies the linear approach may be an acceptable estimation of ground response for practical problems of interest [16]. The equivalent linear model provides few parameters that represent typical soil behavior when subjected to cyclic loading. In the equivalent linear method, an iteration procedure is used to make sure the parameters used in the analysis which are compatible with the computed strain level in all the layers (Fig. 4).

Fig. 4 Spectral shapes for different site conditions [7]





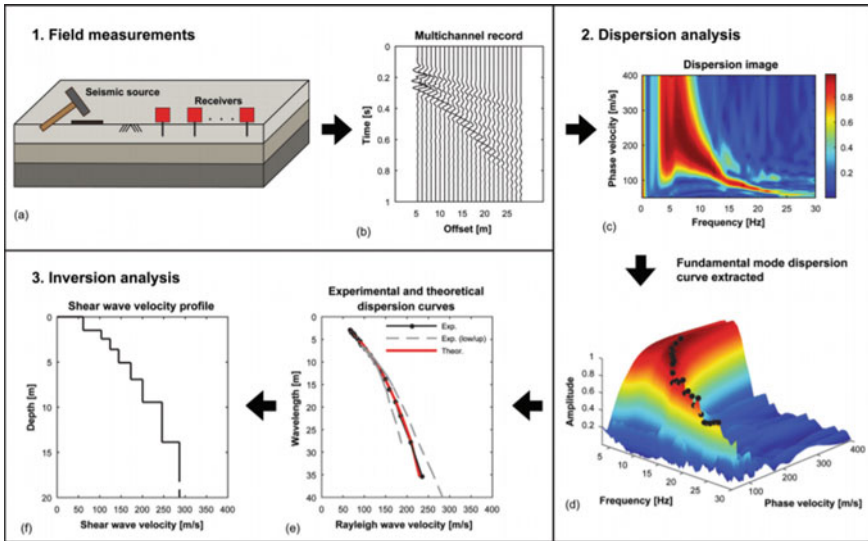


Fig. 5 Procedure followed during MASW survey [22]

Shear wave velocity ( $V_s$ ) is an essential parameter for evaluating the dynamic properties of soil in the shallow subsurface [8, 19]. Several geophysical methods have been proposed for near-surface characterization and measurement of shear wave velocity by using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely used technique is Multichannel Analysis of Surface Waves (MASW). The MASW method was first introduced in geophysics by [20, 21]. Following Fig. 5 represents the steps considered while doing geophysical survey using MASW.

Characteristics of strong ground motion and ground response analysis for different sites in Nanded city of the Maharashtra state studied using MASW [20, 23]. Shear wave velocity averaged over top 30 m of the soil is obtained from MASW survey at 60 sites at depths of 20–50 m below the ground surface. The high  $V_{S30}$  values (900–1000 m/s) are found toward the northeast and southern part of the city. Around the Chikhli Khurd and Shrinagar areas observed shear wave velocity is 500 m/s. The eastern phase areas are characterized by relatively low  $V_{S30}$  values (<200 m/s). They are associated with the Godavari River carrying alluvial deposits composed of brown clay with intercalated bands of sand and gravel.

## 6 Summary and Conclusion

Maharashtra state suffered many earthquakes in the past few decades including major events like 1967 Koyna earthquakes and 1993 Latur earthquakes. These earthquakes

caused property damages and killed thousands of people. To study these earthquakes and their post effects, various techniques and methods are used. There are basically two methods used for seismic hazard assessment viz. Deterministic Seismic Hazard Assessment (DSHA) and Probabilistic Seismic Hazard Assessment (PSHA). DSHA is an easy and quick method and provides a simple framework for the evaluation of the worst-case ground motions associated with the catastrophic failure damages of the large engineering structures such as nuclear power plants and large dams based on maximum credible earthquake. The deterministic seismic hazard analysis is always associated with the subjective predictive decisions, regarding for instance the earthquake potential, of the combined opinions and judgments of seismologists, engineers, risk analysts, economists, social scientists, and finally government officials. PSHA is an improvement over DSHA by considering all possible uncertainties into the hazard estimation procedure, arising in magnitude scales; types of earthquake sources and its nature of physical processes; using various kinds of earthquake recurrence models and its inter-model or intra-model assumptions and estimation of strong ground motion using appropriate ground motion prediction equations. MASW is one of the easiest seismic methods that provide highly favorable and competent results. Shear wave velocity obtained from MASW survey gives a new direction toward liquefaction hazard assessment and seismic microzonation.

## References

1. Ameen AAMM (2018) Modeling the 2004 Andaman-Sumatra tsunami and historical tsunamis from Andaman and Nicobar Island: towards estimation of tsunami hazard along the adjoining areas of Indian Ocean. M.Tech., thesis, Indian Institute of Technology Kanpur, India
2. Dasgupta S, Pande P, Ganguly D, Iqbal Z, Sanyal K, Venkatraman NV, Dasgupta S, Sural B, Harendranath L, Mazumdar K, Sanyal S, Roy K, Das LK, Misra PS, Gupta H (2000) Seismotectonic Atlas of India and its environs. Geol Surv India
3. Ansari A, Satake K, Malik JN (2017) Modelling the 2004 Indian Ocean Tsunami to estimate tsunami heights and its amplitude and to study its effects on coastal areas. ERI Earthquake Conference, University of Tokyo, Japan
4. IS 1893: Part 1.: Indian standard criteria for earthquake resistant design of structures, part—1, general provisions and buildings. Bureau of Indian Standards, New Delhi, India (2002)
5. Raghukanth STG (2011) Seismicity parameters for important urban agglomerations in India. Bull Earthquake Eng 9(5):1361–1386
6. Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc America 58:1583–1606
7. Finn WD, Iai S, Matsunaga Y (1995) The effects of site conditions on ground motions. In: Proc. of 10th ECEE, pp 2607–2612
8. Huang HC, Tseng YS (2002) Characteristics of soil liquefaction using H/V of microtremors in Yuan-Lin area, Taiwan. Terr Atmos Oceanic Sci 13:325–338
9. Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall Publishers, Englewood Cliffs, New Jersey
10. Reiter L (1990) Earthquake hazard analysis: issues and insights. Columbia University Press, New York, USA
11. Hashash YM, Hook JJ, Schmidt B, John I, Yao C (2001) Seismic design and analysis of underground structures. Tunnelling and underground space technology 16(4):247–293. <https://www.sciencedirect.com/science/article/pii/S0886779801000517>

12. Desai S, Choudhury D (2014) Deterministic seismic hazard analysis for greater Mumbai, India. *ASCE GSP* 234:389–398
13. Seed HB, Idriss IM (1971) Simplified procedure for evaluating soil liquefaction potential. *J Soil Mech Found* 97:1249–1273
14. Seed HB, Idriss IM, Arango I (1983) Evaluation of liquefaction potential using field performance data. *J Geotech Eng ASCE* 109(3):458–482
15. Iwasaki T, Tokida K, Tatsuoka F, Watanabe S, Yasuda S, Sato H (1982) Microzonation for soil liquefaction potential using simplified methods. In: *Proceedings, 3rd international conference on microzonation*, Washington D.C., National Science Foundation, pp 1319–1330
16. Luna R, Frost JD (1998) Spatial liquefaction analysis system. *J Comput Civil Eng* 12:48–56
17. Dixit J, Dewaikar DM, Jangid RS (2012) Assessment of liquefaction potential index for Mumbai city. *Nat Hazards Earth Syst Sci* 12:2759–2768
18. Faccioli E (1976) A stochastic approach to soil amplification. *Bull Seismol Soc Am* 66(4):1277–1291
19. Gouveia F, Lopes I, Gomes RC (2016) Deeper  $V_S$  profile from joint analysis of Rayleigh wave data. *Eng Geol* 202:85–98
20. Park CB, Miller RD, Xia J (1999) Multi-channel analysis of surface waves. *Geophys J* 64(3):800–808
21. Park CB, Miller RD, Rydén N, Xia J, Ivanov J (2005) Combined use of active and passive surface waves. *J Environ Eng Geophys* 10(3):323–334
22. Olafsdottir EA, Erlingsson S, Bessason B (2018) Tool for analysis of multichannel analysis of surface waves (MASW) field data and evaluation of shear wave velocity profiles of soils. *J. Canadian Geotech Eng* 55:217–233
23. Subhadra N, Padhy S, Prasad P, Seshunarayana T (2015) Site-specific ground motion simulation and seismic response analysis for microzonation of Nanded City, India. *Nat Hazards* 78:915–938