Nat Hazards (2015) 78:1997–2015
DOI 10.1007/s11069-015-1816-5

ORIGINAL PAPER

Evaluation of seismic hazard and potential of earthquake-induced landslides of the Nilgiris, India

S. Elayaraja[1] · S. S. Chandrasekaran[1] · G. P. Ganapathy[2]

Received: 23 December 2014 / Accepted: 18 May 2015 / Published online: 3 June 2015

Abstract The Nilgiris district in the Tamilnadu state of India is frequented by many landslides in the recent past. Though many of these landslides are rainfall-induced, there is a need to evaluate the potential of earthquake-induced landslides considering seismicity of the region. In this paper, deterministic seismic hazard of Nilgiris is carried out by considering a study area of 350 km radius around Nilgiris. Seismotectonic map of the Nilgiris, showing the details of faults and past earthquakes, is prepared. The peak ground acceleration (PGA) at bed rock level and response spectrum are evaluated. The potential sources for Nilgiris are Moyar and Bhavani shears. The PGA at bed rock level is 0.156 g corresponding to maximum considered earthquake 6.8. Ground response analysis for seven sites, in the Nilgiris, is carried out by one-dimensional equivalent linear method using SHAKE 2000 program after considering the effect of topography. PGA of surface motion got amplified to 0.64 g in Coonoor site and 0.44 g in Ooty site compared to 0.39 g of the input motion. The bracketed duration of time history of surface acceleration has increased to 20 s in Coonoor site and 18 s in Ooty site compared to that of 8 s of input motion. Results from seismic displacement analysis using Newmark's method revealed that out of seven sites investigated, five sites have moderate seismic landslide hazard and two sites (Coonoor and Ooty) have high hazard.

Keywords Seismic hazard · Response spectrum · Ground response · Seismic displacement · Earthquake-induced landslide

✉ S. S. Chandrasekaran
sschandrasekaran@yahoo.co.in; sschandrasekaran@gmail.com; chandrasekaran.ss@vit.ac.in

[1] Geotechnical Engineering, SMBS, VIT University, Vellore 632014, India

[2] CDMM, VIT University, Vellore 632014, India

1 Introduction

Earthquake-induced landslide is one of the very important geotechnical hazards associated with earthquake which affect large areas (Rodriguez et al. 1999). In few earthquakes such as Peruvian earthquake of 31 May 1970, almost half the fatalities were due to landslides (Rodriguez et al. 1999; Lomnitz 1970). Recent examples of extensive devastations caused due to earthquake-induced landslides are 2011 Sikkim earthquake in India (Martha et al. 2014) and 2008 Wenchuan earthquake in China. Budimir et al. (2014) observed that combined effects of earthquakes and landslides resulted in more fatalities than earthquakes alone around the World. The potential of earthquakes with shallow focal depths in triggering landslides is highlighted by Rodriguez et al. (1999) and Sepulveda et al. (2008).

The seismicity of India is characterized by both relatively high frequency of large earthquakes and relatively low frequency of moderate earthquakes (Lai et al. 2009). Due to infrequent nature of moderate earthquakes, the seismic problem does not receive due attention given the overall earthquake potential of India. Peninsular India (PI), the southern peninsular part of India, is long believed to be Stable Continental Region (SCR) of the Indo-Australian tectonic shield. But, recent devastating intraplate events in the PI (e.g., Koyna earthquake in 1967 M_w 6.7; Lattur earthquake in 1993 M_w 6.1; Jabalpur earthquake in 1997 M_w 5.8; Bhuj earthquake in 2001 M_w 7.7 etc.), apart from number of moderate seismic events (e.g., Pondicherry 2001 M_w 5.5, Ambur 2008 M_w 3.8, Dharapuram 2011 M_w 3, Tiruchirapalli 2012 M_w 3.6, Dharmapuri 2012 M_w 3.3) have disproved this notion. Intraplate events, though rarer than plate boundary events, usually tend to be more harmful (Raghu Kanth and Iyengar 2006). Though seismic hazard in PI is less severe than in the Himalayan region, the damages caused due to intraplate events are generally very high due to lack of earthquake-resistant construction (NDMA 2010; Menon et al. 2010). These intraplate events are also felt over a much larger area than the Himalayan earthquakes (Singh et al. 2004; Kayal 2008; NDMA 2010). This is because the earthquakes in PI are shallow, having focal depths <25 km (Singh et al. 2004; Mandal et al. 2000; NDMA

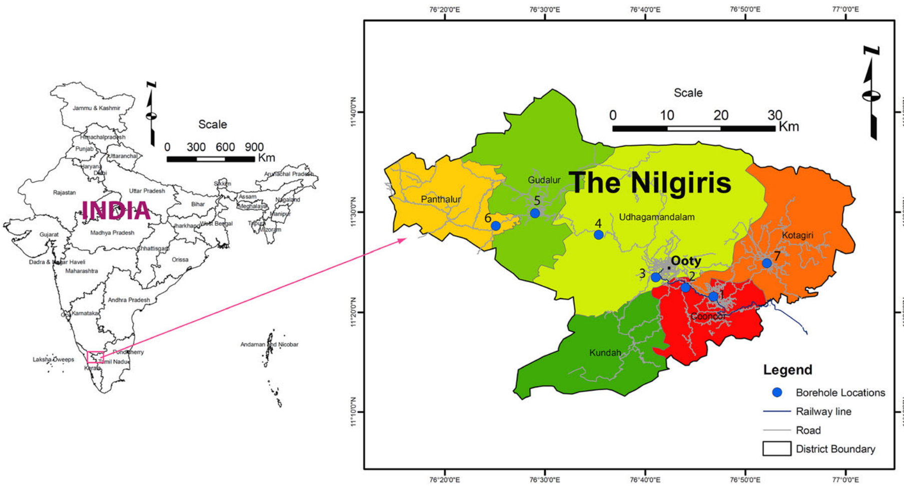


Fig. 1 Location of study area

2010). Recent moderate events (Pondicherry 2001 M_w 5.5—focal depth of 25 km, Tiruchirapalli 2012 M_w 3.6—10 km, Dharmapuri 2012 M_w 3.3—15 km) give more proof to this.

Several researchers emphasized the importance of evaluation of proper seismic input in the analysis of shallow (e.g., Gazetas and Mylonakis 2005) and pile foundations (e.g., Finn et al. 1997; Chandrasekaran et al. 2013a). Few studies on seismic hazard assessment of entire PI are reported in the literature (e.g., Kaila and Rao 1979; Basu and Nigam 1977; Khattri et al. 1984; Parvez et al. 2003; Jaiswal and Sinha 2007). In the recent past, few studies have been reported on specific regions with in the peninsula (e.g., Mumbai: Raghu Kanth and Iyengar 2006; Bangalore: Sitharam and Anbazhagan 2007; Chennai: Boominathan et al. 2008; Uma Maheswari et al. 2010; Chethanamba and Dodagoudar 2012; Kanchipuram: Lai et al. 2009; Kalyan Kumar and Dodagoudar 2011; Tamilnadu: Menon et al. 2010).

Nilgiris district, located in the state of Tamilnadu, in PI is affected by numerous landslides historically (Bhandari 2006; NDMG 2009; Chandrasekaran et al. 2013b). The location of the Nilgiris is shown in Fig. 1. The Nilgiris district is a hilly terrain with altitude range of 900–2640 m. The Nilgiris is an important tourist center in southern India, served by the Nagapattinam—Gudalur National Highway (NH67) and Nilgiri Mountain Railway (NMR) line which was declared as World Heritage site by UNESCO. Ooty city is the headquarters of Nilgiris district and the district borders with three state of India, namely Tamilnadu, Karnataka and Kerala. The hilly terrain also spreads in all these three states. Dodabetta and Ootacamund are two types of landforms in the Nilgiris. The Nilgiris district is in the tropical zone, and hills have thick soil cover up to 40 m at few locations. The soils in most part of the Nilgiris are deeply weathered (Seshagiri et al. 1982; Rajakumar et al. 2007). Most of the landslides in Nilgiris occurred during monsoon seasons and are predominantly rainfall-induced (NDMG 2009; Jaiswal et al. 2011; Chandrasekaran et al. 2013b; Ganapathy and Rajawat 2015). Though most of the landslides in Nilgiris are rainfall-induced, it is pertinent to note that the Nilgiris is classified in Seismic Zone III (IS 1893–2002). The expected ground motion corresponding to maximum considered earthquake is 0.16 g (IS 1893–2002; Menon et al. 2010). Significant earthquakes (e.g., Ooty M_w 6.2 in 1882, Palghat M_w 6.2 in 1900, Ernakulam M_w 5 in 1953, Coimbatore M_w 5 in 1972) have occurred at or near this district in the past (SEISAT ; MoES 2009). Recent moderate events (e.g., Kottayam M_w 5 in 2000, Dharapuram M_w 3 in 2011) and investigations of Menon et al. (2010), Ganapathy and Rajarathnam (2010) have brought out the seismic activeness of the region. It is important to note that most of the events at or near Nilgiris are having shallow focal depths. Considering the above facts, there is a need to evaluate the potential of earthquake-induced landslides in the Nilgiris. Hence, in the present study, seismic hazard, ground response and seismic displacement analyses are carried out for the Nilgiris.

2 Methodology

The methodology adopted in this study consists of four phases. In the first phase, seismic hazard of the study area is analyzed using deterministic approach. Seismotectonic map of the study area is prepared by considering 350 km radius (Anbazhagan et al. 2009) with Ooty city as center. The peak ground acceleration (PGA) and response spectrum are evaluated using attenuation relationship. In the second phase, geotechnical investigation is carried out by making boreholes at seven locations in the district and by conducting field and laboratory tests on soil. Various properties including shear wave velocity of the soil profile are obtained. In the third phase, ground response analysis is carried by giving due consideration to topography. In the last phase, seismic displacement of slopes is determined by Newmark's method. Finally, the hazard potential of earthquake-induced landslides is evaluated, for various locations, based on the obtained seismic displacement. The following section presents the adopted methodology in detail, results and discussion.

3 Analysis, results and discussion

3.1 Deterministic seismic hazard analysis (DSHA)

The deterministic method of seismic hazard analysis involves in finding the maximum possible ground motion at a site by taking into account the seismotectonic setup of the area around the site and the available data on past earthquakes in the area (Krinitzsky 1995; Romeo and Prestininzi 2000). Deterministic approach is adopted in this study in view of

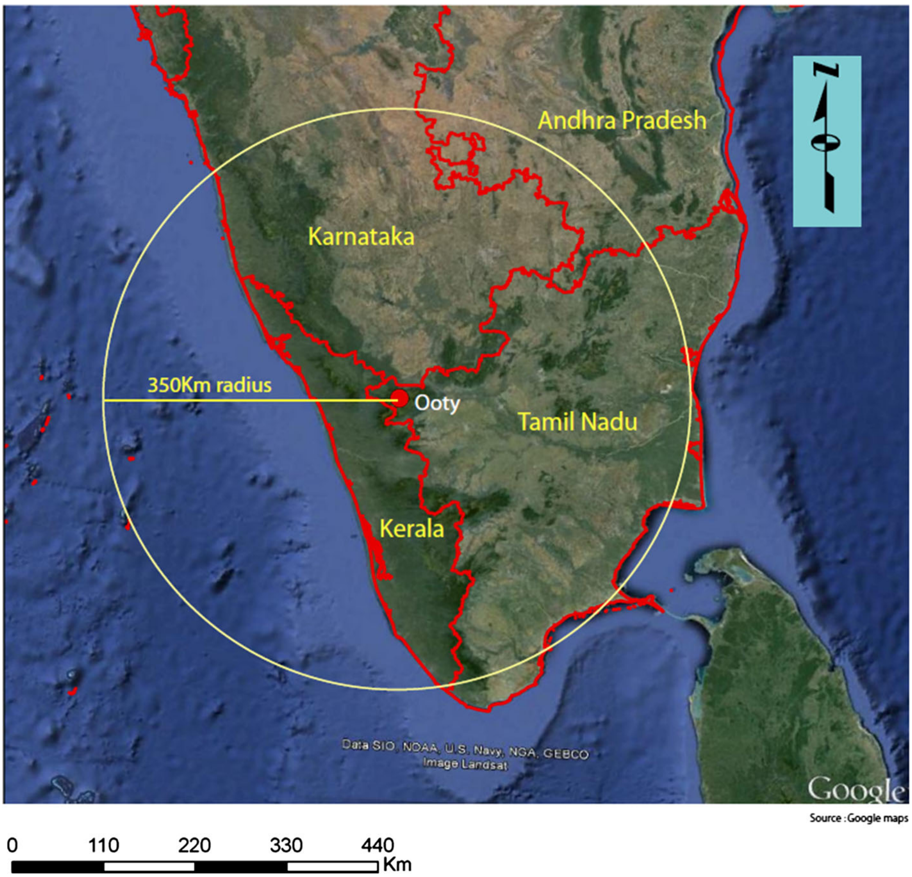
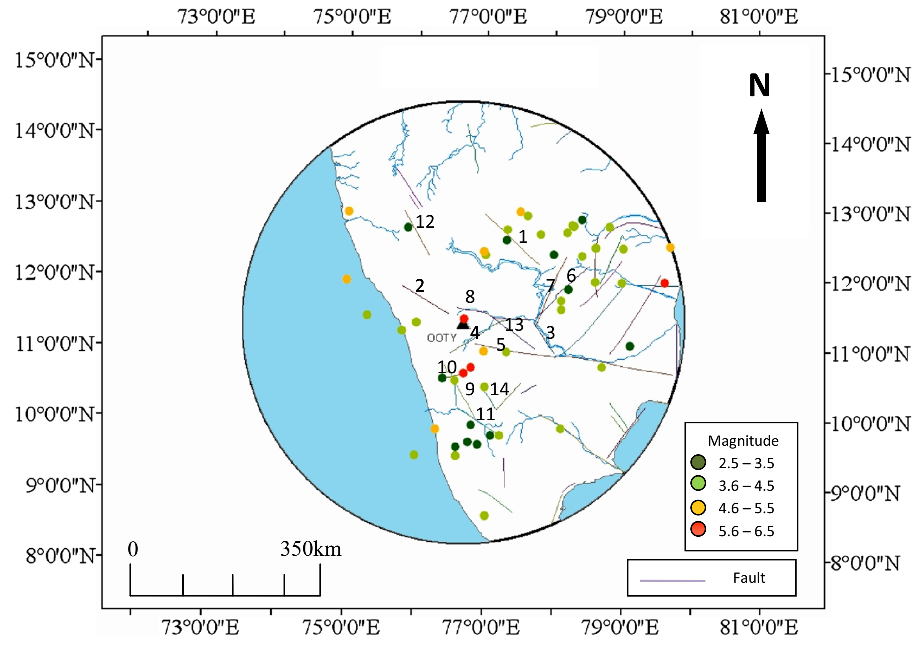


Fig. 2 Region of 350 km radius considered around study area

the limited seismological data on strong ground motion for the study area (Parvez et al. 2003).

Experience from past earthquakes show that a site vibrates due to earthquake events occurring in a region of about 300–350 km radius around the site (NDMA 2010; Sitharam and Anbazhagan 2007). The area of 350 km radius, having Ooty city—the headquarter of Nilgiris district (with latitude of 11.41°N and longitude of 76.7°E)—as center point, is considered for the hazard analysis (Fig. 2). It is also pertinent to note that the epicenter M_w 6, 1882 earthquake was at Ooty city. The study area lies between latitudes 8.2° north to 14.5° north and longitudes 73.8° east to 79.9° east. The study area covers major part of Tamilnadu, portion of Arabian Sea, parts of Kerala and Karnataka. Seismotectonic details of India such as geology, rock type, fault orientation, lineaments and shear zones with earthquake events are well documented in the Seismotectonic Atlas of India (SEISAT). In the present analysis, six SEISAT sheet maps are merged to cover the seismic sources within 350 km radius around Ooty (Fig. 2). Seismotectonic map of the Nilgiris showing the details of faults and past earthquakes has been prepared using ArcGIS9 software and is



Fault No	Fault Name	Fault No	Fault Name
1	Arkavati fault	8	Moyar Shear
2	Bhavali fault	9	Ottapalam - Kuttampuzha fault
3	Bhavani-Kanumudi fault	10	Pattikad-Kollengol fault
4	Bhavani Shear	11	Periyar fault
5	Cauvery fault	12	Sakleshpur-Bettadpur fault
6	Main fault	13	Tiruppur fault
7	Mettur east fault	14	Valparai - Anaimudi fault

Fig. 3 Seismotectonic map of Ooty and its surroundings

Table 1 Calculated peak horizontal acceleration at bed rock level

Sl. no.	Name of the fault	Length of the fault (km)	Max. occurred earthquake (M_w)	Hypocentral distance from Ooty (km)	PGA (g) (based on maximum occurred earthquake)	PGA (g) (based on maximum occurred earthquake + 0.5)	PGA (g) (based on maximum potential earthquake $M_w = 6.8$)
1.	Arkavati fault	120.24	4.7	143.87	0.001	0.003	0.018
2	Bhavali fault	86.90	6.2	37.42	0.064	0.101	0.109
3	Bhavani-Kanumudi fault	61.90	4.7	99.09	0.002	0.004	0.030
4	Bhavani Shear	102.38	6	29.26	0.071	0.112	0.141
5	Cauvery fault	326.19	5.4	40.51	0.023	0.042	0.099
6	Main fault	121.43	4.9	109.66	0.003	0.005	0.027
7	Mettur east fault	121.43	4.6	108.48	0.002	0.004	0.027
8	Moyar Shear	119.05	6	26.43	0.080	0.125	0.156
9	Ottapalam-Kuttampuzha fault	92.86	4.2	74.58	0.002	0.004	0.046
10	Pattikad-Kollengol fault	40.48	6.2	74.58	0.025	0.042	0.046
11	Periyar fault	83.33	4.8	132.05	0.002	0.003	0.021
12	Sakleshpur-Bettadpur fault	83.33	4	121.43	0.001	0.001	0.023
13	Tiruppur fault	85.71	4.29	43.90	0.005	0.010	0.091
14	Valparai-Anaimudi fault	44.05	4.5	101.43	0.002	0.003	0.029

shown in Fig. 3. The map consists of 39 faults with lengths ranging from 26 to 326 km. Most of the past earthquake events are associated with one or more of these faults. The details of important faults are listed in Table 1. The study area comprises of major tectonic domains: Dharwar Craton, Kolar–Cuddapah–Eastern Ghat sector, Pandyan Mobile Belt, Southern Granulite Terrain (SGT) Craton, Palghat Cauveri Shear. The basement around Ooty comprises of high-grade gneiss granulite.

Many earthquakes have been reported in this region, and the first-reported seismic activity in the study area had a magnitude M_w 4.3 (SEISAT ; MoES 2009) occurred in 1819. Earthquake catalog was prepared for the 350 km radius around Ooty for a period from 1819 to 2014. The major sources of earthquake data are Indian Meteorological Department (IMD 2012) and reports (SEISAT) of the Geological Survey of India (GSI), USGS National Earthquake Information Center (NEIC), Sitharam and Anbazhagan (2007), Kalyan Kumar and Dodagoudar (2011), Lai et al. (2009) and Uma Maheswari et al. (2010). The obtained earthquake data are declustered using static window method. It is the method of removing foreshocks and aftershocks of a particular earthquake with respect to constant time and distance. Based on the characteristics of our area of study, 1-month duration and 30 km radius are considered for removal of foreshocks and aftershocks. The earthquake events, collated with latitudes and longitudes, are shown in Fig. 3. The epicenters and magnitudes of earthquakes that are occurred for past 200 years in the study area are also shown in Fig. 3. A total of 47 events greater than M_w 2.5 are depicted in the figure. The data set contains 12 events with M_w varying from 2.5 to 3.5, 25 events of M_w from 3.6 to 4.5, 6 events of M_w from 4.6 to 5.5, 4 events of M_w from 5.6 to 6.5. The important events are Ooty earthquake (1882) M_w 6.2, Palghat earthquake (1900) M_w 6.2 (MoES 2009).

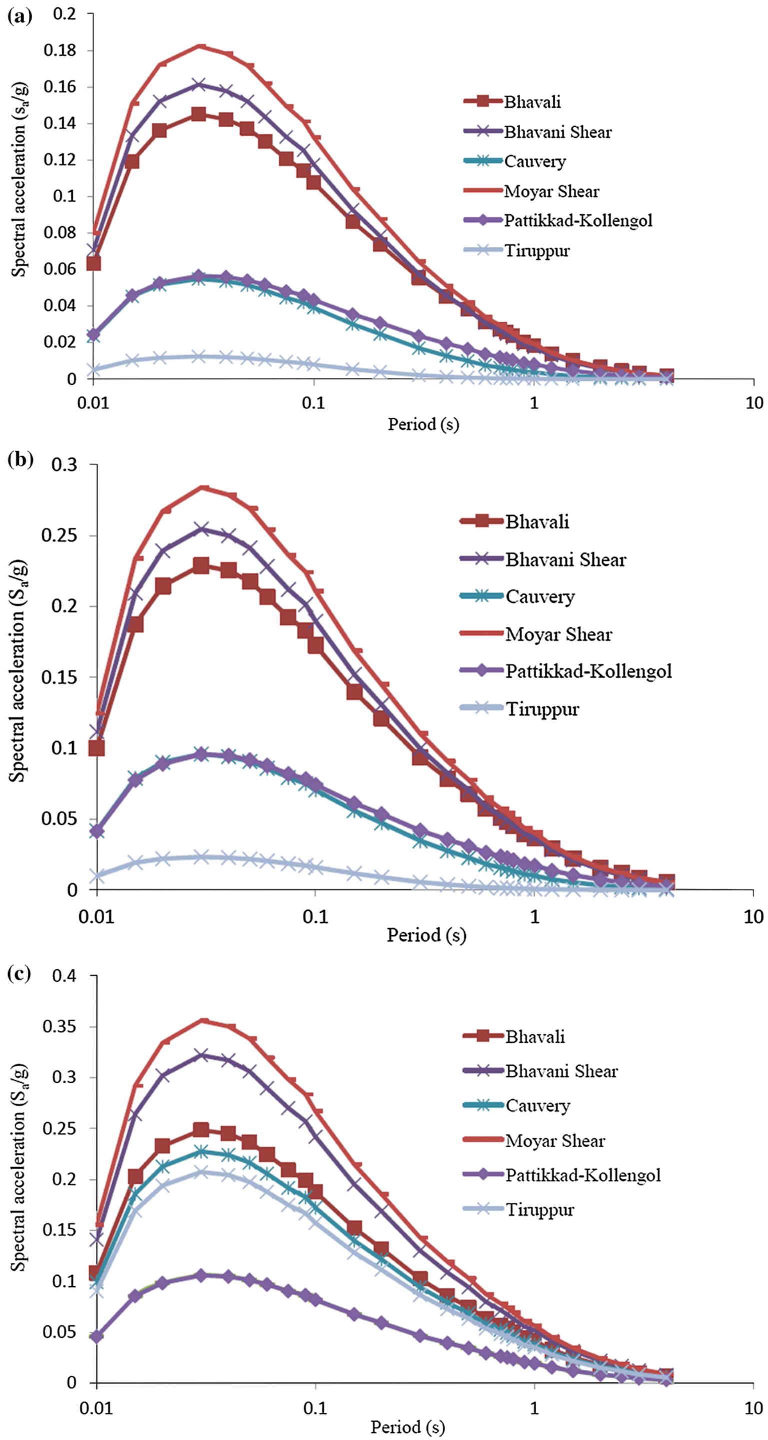
In the present study, only line sources are considered and all known activities are attributed to mapped faults only. It can be seen from Fig. 3 that epicenters of earthquakes of past 200 years fall in the region of various faults or nearer to it viz Arkavati fault, Bhavali fault, Bhavani-Kanumudi fault, Bhavani shear, Cauvery fault, Main fault, Mettur East fault, Moyar shear, Ottapalam-Kuttampuzha fault, Pattikad-Kollengol fault, Periyar fault, Sakleshpur-Bettadpur fault, Tiruppur fault, Valparai-Anaimudi fault, which indicates that these faults are active.

Knowledge of the attenuation of the chosen ground motion parameter as a function of earthquake magnitude and distance is essential for site-specific analysis of seismic hazard (Tsapanos et al. 2011). The following attenuation relationship for PI recommended by National Disaster Management Authority (NDMA 2010) is used in the present study.

$$\begin{aligned} \ln(S_a/g) &= C_1 + C_2M + C^3M^2 + C_4r + C_5\ln\left(r + C_6e_7^{CM}\right) + C_8\log(r)f_o + \ln(\varepsilon) \\ f_o &= \max(\ln(r/100), 0) \end{aligned} \quad (1)$$

where S_a is the spectral acceleration, M is the moment magnitude, r is the hypocentral distance in kilometers. This attenuation relation accounts for geometrical spreading, anelastic attenuation and magnitude saturation (NDMA 2010). The coefficients of the above equation for PI as obtained by NDMA (2010) following Joyner and Boore (1981), NDMA (2010) are used in the present study.

Shortest distances from various sources to Ooty city have been measured from the seismotectonic map Fig. 3. Since earthquakes in PI are shallow having focal depth of 5–25 km (Singh et al. 2004; Sitharam and Anbazhagan 2007; Lai et al. 2009), focal depth of 15 km is considered for calculating hypocentral distances. It is to be noted that focal


(a)
Spectral acceleration (Sa/g)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.01
0.1
1
10
Period (s)
Bhavali
Bhavani Shear
Cauvery
Moyar Shear
Pattikkad-Kollengol
Tiruppur
(b)
Spectral acceleration (Sa/g)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.01
0.1
1
10
Period (s)
Bhavali
Bhavani Shear
Cauvery
Moyar Shear
Pattikkad-Kollengol
Tiruppur
(c)
Spectral acceleration (Sa/g)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.01
0.1
1
10
Period (s)
Bhavali
Bhavani Shear
Cauvery
Moyar Shear
Pattikkad-Kollengol
Tiruppur

◀**Fig. 4** Response spectrum corresponding to different faults for: **a** maximum occured earthquake, **b** maximum occured earthquake plus 0.5 and **c** maximum potential magnitude (M_{max} 6.8)

depths of recent earthquakes in the study area are shallow: 10 km for Trichy 2012, 15 km for Dharmapuri 2012, 33 km for Ambur 2008 and Ariyalur 2011 events.

The PGA at bed rock level is calculated for the maximum occurred earthquake of each source using the attenuation relation (Eq. 1) and presented in Table 1. It can be seen from Table 1, PGA value ranges from 0.001 to 0.080 g for the maximum occurred earthquake. The response spectrum obtained using attenuation relation Eq. (1) for maximum occurred earthquake corresponding to different faults is shown in Fig. 4a. The Moyar Shear with maximum occurred earthquake of M_w 6 has the highest PGA of 0.080 g (Table 1; Fig. 4a). The predominant period of the response spectrum corresponding to Moyar shear is 0.03 s, and peak spectral acceleration is 0.182 g (Fig. 4a).

In the absence of source parameters, an increment of about 0.25–1 to the largest historical earthquake magnitude is usually considered (Uma Maheswari et al. 2010). At present in the study area, the properties and the rupture characteristics of the faults are not well established and hence in the hazard analysis, the largest observed magnitude for each seismic source is increased by 0.5 units to arrive at the maximum possible magnitude (Kijko and Graham 1998; Boominathan et al. 2008). The peak horizontal acceleration at bed rock level is calculated for magnitude of maximum occurred earthquake plus 0.5 for each source and presented in Table 1. It can be seen from Table 1, PGA value ranges from 0.001 to 0.125 g for the maximum occurred earthquake plus 0.5. The response spectrum obtained for magnitude of maximum occurred earthquake plus 0.5 for different faults are shown in Fig. 4b. The Moyar shear gives highest PGA of 0.125 g followed by Bhavani shear with 0.112 g (Table 1; Fig. 4b). The predominant period of the response spectrum corresponding to Moyar shear is 0.03 s, and peak spectral acceleration is 0.284 g (Fig. 4b).

NDMA (2010) classified India into 32 seismogenic zones based on historical seismicity, geology and tectonic features. The maximum potential magnitude of earthquake (M_{max}) for Nilgiris region (zone 29, Southern Craton) estimated by NDMA (2010) using the method of maximum likelihood in Kijko's (Kijko and Graham 1998) approach is 6.8 (NDMA 2010). The peak horizontal acceleration at bed rock level is calculated for M_{max} of 6.8 for all the sources and presented in Table 1. It can be seen from Table 1, PGA value ranges from 0.018 to 0.156 g for the M_{max} 6.8. It can be observed that Moyar shear have yielded PGA of 0.156 g followed by Bhavani shear 0.141 g. This PGA value (0.156 g) for Nilgiris is comparable to Indian Standard code (IS 1893–Part I 2002) value of 0.16 g and probabilistic seismic hazard (Menon et al. 2010) value of 0.164 g. The response spectrum obtained for M_{max} 6.8 is shown in Fig. 4c. The predominant period of the response spectrum corresponding to Moyar Shear is 0.03 s, and peak spectral acceleration is 0.356 g. It can be observed from the results of DSHA that the potential sources for Nilgiris are Moyar and Bhavani Shears. The maximum considered earthquake (MCE) is the maximum potential magnitude of M_{max} 6.8. The PGA at bed rock level is 0.156 g.

3.2 Geotechnical investigation

Geotechnical investigations are conducted by making boreholes at seven sites (Coonoor, Ooty, Gudalur, Ketti, Kothagiri, Naduvattam and Panthalur) well spread over to reasonably cover entire Nilgiris district. The locations of sites investigated are shown in Fig. 1 and Table 2. Bore holes are made up to bedrock at each site. Standard penetration tests (SPT)

Table 2 Seismic displacements of slopes at various sites and their hazard potential

Borehole no.	Borehole location	Seismic displacement of slope (cm)	Hazard potential
1	Conoor	7.38	High
2	Ketti	4.66	Moderate
3	Ooty	5.78	High
4	Naduvattam	4.48	Moderate
5	Gudalur	4.70	Moderate
6	Panthalur	4.39	Moderate
7	Kothagiri	4.52	Moderate

were conducted as per IS 2131-2002 at different depths in the bore holes. Extensive laboratory investigations were carried out on undisturbed and disturbed soil samples collected. Specific gravity, liquid limit, plastic limit, sieve analysis of soil samples were carried out as per relevant ASTM standards. The soil samples were classified as per Unified Soil Classification System (ASTM D2487-11). Borelogs showing soil profiles of Coonoor and Ooty sites are depicted in Fig. 5. The shear wave velocity (V_s) (in m/s) of soil layers is estimated from SPT N value using the following correlation proposed by Anbazhagan et al. (2012)

$$V_s = 68.96\,N^{0.51}. \tag{2}$$

3.3 Ground response analysis

Local site conditions profoundly influence most of the characteristics of the ground motion during an earthquake. The extent of this modification depends on the geometry of the soil profile, thickness and properties of the soil profile and characteristics of the input motion (Kramer 1996; Lai et al. 2009). The strong influence of geological and a geotechnical characteristic of the site on the nature of the ground shaking were clearly demonstrated in various earthquakes (e.g., 1985 Mexico earthquake, 1988 Spitak earthquake, 1989 Loma Prieta earthquake, 1995 Kobe earthquake and 1999 Kocaeli earthquake) (Durukal 2002; Ansal 2004).

The peak horizontal acceleration (PGA) value of 0.156 g at bed rock level, obtained from DSHA, is used in the ground response analysis. Since the study area Nilgiris is a hilly region having altitude range between 900 and 2640 m, the effect of topography need to be considered in the ground response analysis. Trifunic and Hudson (1971) have brought out the topographic effect on the response of Pacoima Dam in southern California. Ansal (2004) opined that quantification of topographic effects on seismic ground motion is a very difficult task considering the complexity of parameters involved.

For a triangular infinite wedge subjected to vertically propagating horizontally polarized shear (SH) waves, apex displacements are amplified by a factor $2\pi/\varphi$, where φ is the apex angle (Fig. 6). This approach is used to approximate topographic effects for certain cases of ridge valley terrain (Geli et al. 1988; Sanchez-Sesma 1982; Faccioli 1991; Kramer 1996). Since for a crest φ is always lesser than π, the amplification factor will always be >2. Increased amplification near crest of a ridge was measured in five earthquakes in Matsuzaki, Japan by Jibson (1987). The average peak crest acceleration was about 2.5 times the average base acceleration (Jibson 1987). Hence, in the present study

(a)

Depth below GL(m)	Soil profile	Description of soil stratum	Depth at which SPT conducted (m)	SPT(N) Value	Unit weight (kN/m^3)
0.00		Silty sand (SM)	1.5	7	19.6
			3.0	12	
			4.5	8	
			6.0	14	
			7.5	11	
9.0			9.0	17	
10.5		Soft disintegrated rock	10.5	39	23.7
		Hard rock			

(b)

Depth below GL (m)	Soil profile	Description of Soil	Depth at which SPT conducted (m)	SPT(N) Value	Unit weight (kN/m^3)
0.00		Silty sand (SM)	0.9	9	19.2
			2.4	12	
			3.9	11	
			5.4	13	
6.9			6.9	8	
		Soft disintegrated rock	8.4	27	22.1
			9.9	25	
			11.4	38	
12.7			12.7	29	
		Hard rock			

Fig. 5 Soil profiles at sites: **a** Coonoor and **b** Ooty

amplification factor of 2.5 is used to account for effect of topography (Fig. 6). Thus, PGA value of 0.156 g at bed rock level obtained from DSHA is multiplied by 2.5 which yielded PGA value of 0.39 g. This PGA value is given as an input at bottom of the soil layers/

Fig. 6 Effect of topography and idealization of hill in study area

bedrock in the ground response analysis carried out by one-dimensional equivalent linear method using SHAKE 2000 program. The input data include the acceleration time history at bedrock, shear wave velocity, modulus reduction and damping curves of soil layers. Due to non-availability of strong motion data in the study region, Carbondale earthquake-simulated motion, available in SHAKE 2000, is taken as input motion at bed rock level. The characteristics of this earthquake motion (Moment Magnitude—6.1, focal depth—4 km, PGA—0.1 g) reasonably match with max potential magnitude of 6.8 and PGA of 0.156 g obtained from DSHA in the present investigation for the study area. The Carbondale earthquake-simulated motion is scaled to get PGA value of 0.39 g. The acceleration time history of input motion is depicted in Fig. 7a. The Fourier spectrum of input motion is shown in Fig. 7b. It can be noticed from the figure that the concentration of maximum energy is observed between 2 and 25 Hz. The predominant frequency is 5 Hz. The standard modulus reduction and damping curves proposed by Seed and Idriss (1970) and Seed et al. (1976) are used for sand and gravel layers, respectively, in the ground response analysis. Schnabel (1973) modulus reduction and damping ratio curves are used for the rock.

The acceleration time histories at surface (ground level) of the Coonoor and Ooty sites are shown in Fig. 8. It can be noticed from Fig. 8 that PGA amplified to 0.64 g in Coonoor site (Fig. 8a) and 0.44 g in Ooty site (Fig. 8b) compared to 0.39 g of the input motion at bed rock. It can also be observed that the bracketed duration (Bolt 1969) (time between first and last exceedances of threshold acceleration of 0.05 g) of time history of surface acceleration has increased to 20 s in Coonoor site (Fig. 8a) and 18 s in Ooty site (Fig. 8b) compared to that of 8 s of input motion (Fig. 7a).

The ratio of amplitude of motion at ground surface to that of bed rock motion is plotted as amplification spectrum in Fig. 9. It can be observed from the figure that for the stiffer soil at Ooty site (Fig. 9a) the motion in the medium frequency range gets amplified,

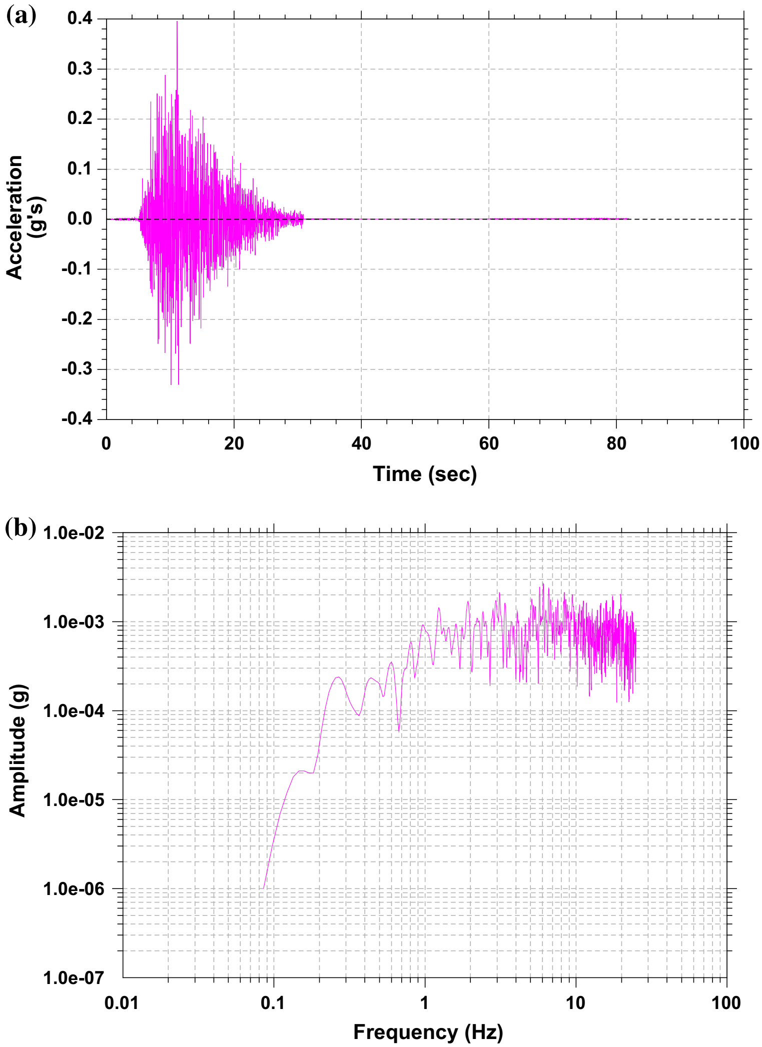


Fig. 7 Input motion: **a** acceleration time history and **b** Fourier spectrum

whereas the softer soil site at Coonoor (Fig. 9b) the low-frequency (long-period) bed rock motion gets amplified (Seed et al. 1976; Boominathan et al. 2008).

3.4 Evaluation of seismic displacement of slopes by Newmark's method

Various methods have been evolved over recent years for investigating stability of slopes during earthquakes. In the present study, Newmark's approach as recommended by Houston et al. (1987) is adopted to estimate the seismic displacement of slopes using SHAKE 2000. Newmark's method for modeling a landslide as a rigid plastic block sliding on an inclined plane provides a workable means of predicting approximate landslide displacements. Newmark's method models a landslide as a rigid plastic friction block

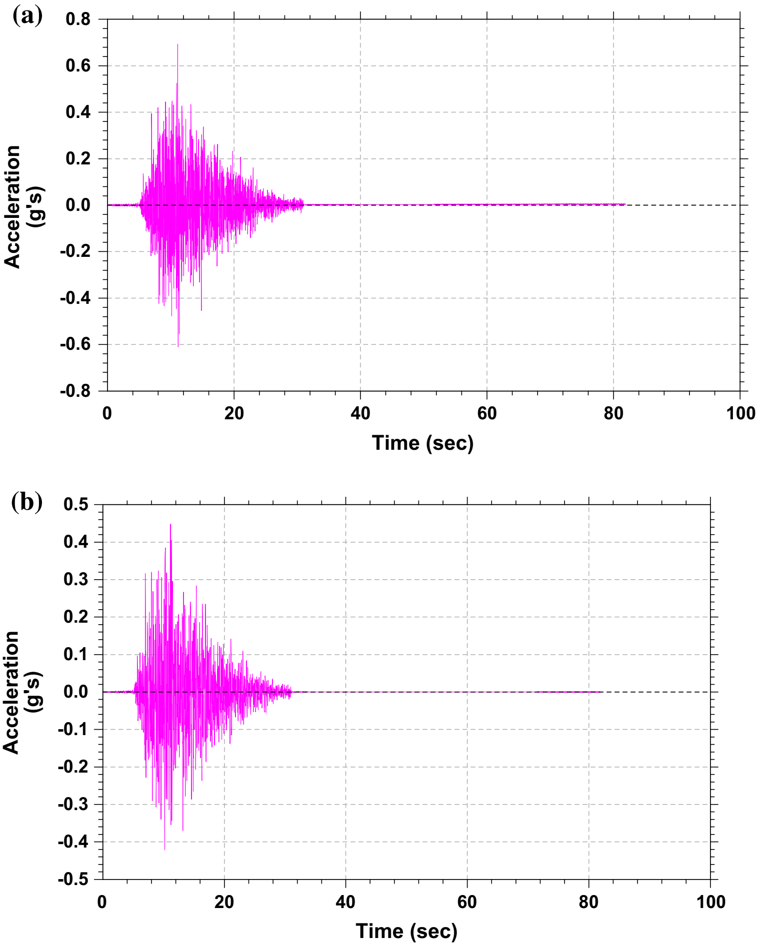


Fig. 8 Time history of surface acceleration at: **a** Coonoor site and **b** Ooty site

having a known yield or critical acceleration and the acceleration required to overcome frictional resistance. The analysis calculates the permanent displacement of the block as it is subjected to the effect of an earthquake acceleration time history. The Newmark's method yields much more useful information than pseudo-static analysis and is far more practical than finite element modeling (Jibson 2011).

The seismic displacement analysis using Newmark's method is carried out for all the seven sites. The acceleration time histories of surface motion (Fig. 8) of various sites obtained from ground response analysis are used as inputs. The yield acceleration for the analysis is 0.05 g considering various geotechnical factors. The acceleration time histories of the surface motion that lie above the yield acceleration are double integrated to determine the permanent landslide displacement. The permanent slope displacements obtained from the analysis are depicted in Fig. 10 for Coonoor and Ooty sites. The displacements of slope at different sites are presented in Table 2.

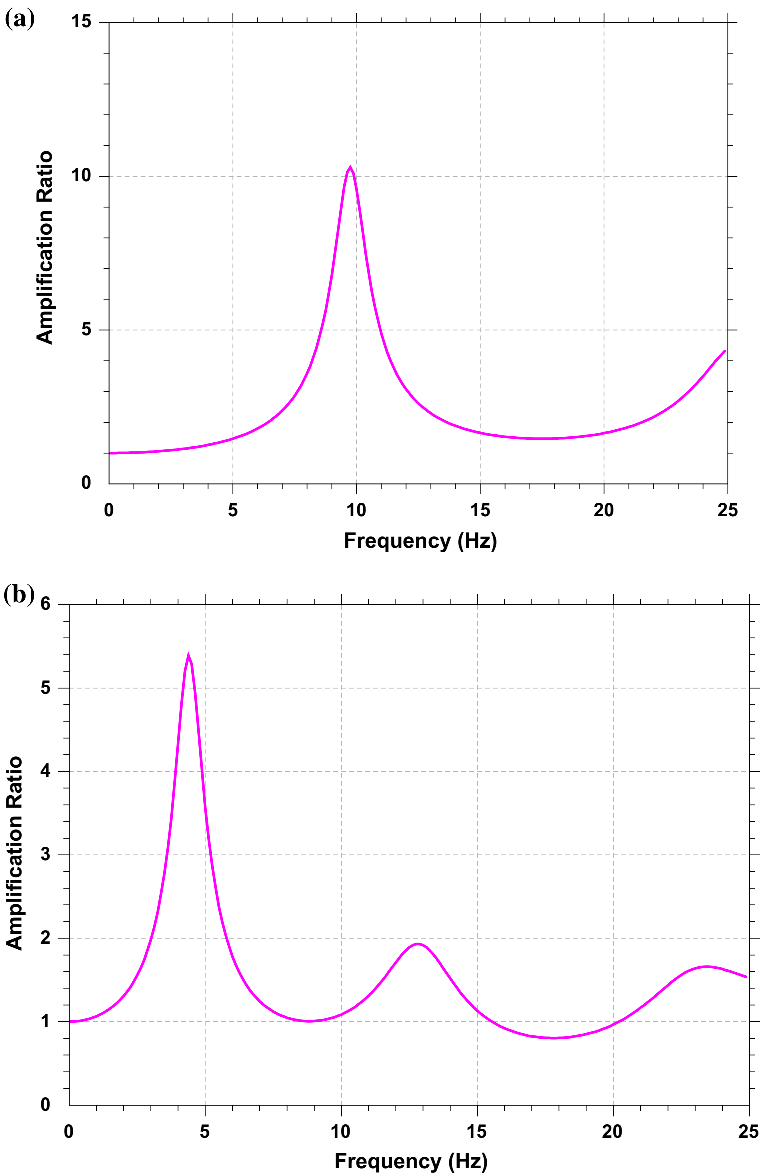


Fig. 9 Amplification spectrum at: **a** Ooty site and **b** Coonoor site

As per the criteria of Jibson (2011), Jibson and Michael (2009), the seismic landslide hazard potential of shallow landslides is related to seismic displacement as: 0–1 cm (low), 1–5 cm (moderate), 5–15 cm (high), >15 cm (very high). The seismic landslide hazard potential of various sites is presented in Table 2. We can notice from the table that five sites have moderate seismic landslide hazard and two sites (Coonoor and Ooty) have high hazard. These two sites need further detailed investigation and suitable slope stabilization measures.

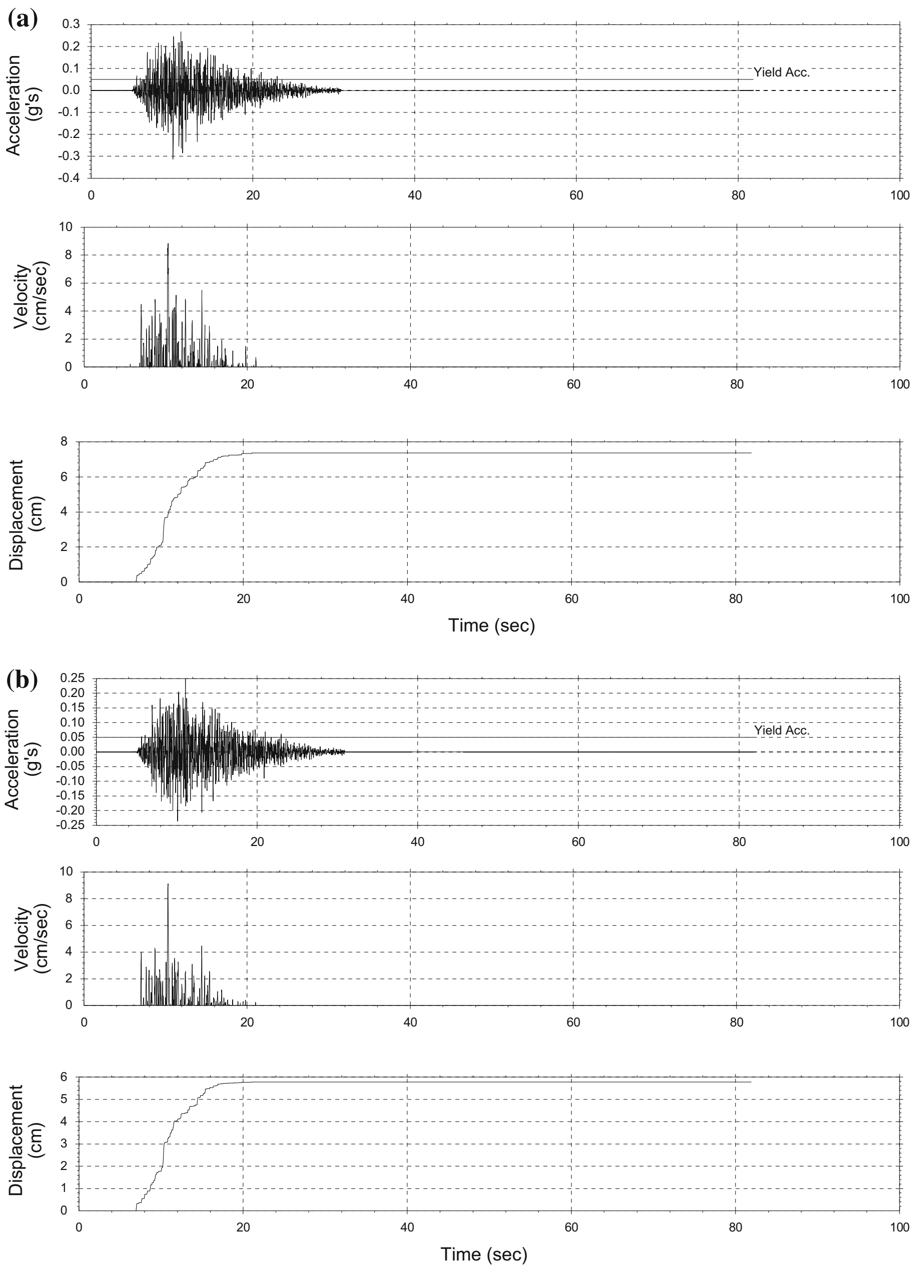


Fig. 10 Displacement of slope (Newmark analysis) at: **a** Coonoor site and **b** Ooty site

4 Conclusions

Seismic hazard analysis of the Nilgiris in Tamilnadu, India, is carried out using deterministic approach. The study area of 350 km radius around Ooty city is considered for the analysis. Seismotectonic map of the Nilgiris showing the details of faults and past earthquakes has been prepared. The peak horizontal acceleration (PGA) at bed rock level and response spectrum is calculated for three cases: maximum occurred earthquake of each source, maximum occurred earthquake plus 0.5 for each source and for maximum potential magnitude (M_{max}) of 6.8 for all the sources. It can be observed from the results of DSHA that the potential sources for Nilgiris are Moyar and Bhavani Shears. The MCE is the maximum potential magnitude of M_{max} 6.8. The PGA at bed rock level is 0.156 g.

Ground response analysis is carried out for the seven sites in Nilgiris by one-dimensional equivalent linear method using SHAKE 2000 program. Amplification factor of 2.5 is used to account for effect of topography. PGA of surface motion got amplified to 0.64 g in Coonoor site and 0.44 g in Ooty site compared to 0.39 g of the input motion. The bracketed duration of time history of surface acceleration has increased to 20 s in Coonoor site and 18 s in Ooty site compared to that of 8 s of input motion.

The seismic displacement analysis using Newmark's method is carried out for all the seven sites. Based on the obtained seismic displacements, the potential of earthquake-induced landslides is assessed. Results reveal that while five sites have moderate seismic landslide hazard, two sites (Coonoor and Ooty) have high hazard. These two sites need further detailed investigation and suitable slope stabilization measures.

Acknowledgments Dr. S. S. Chandrasekaran thanks Department of Science and Technology (DST-NRDMS Division), Government of India, New Delhi, for sponsoring the study reported in this paper through the project "Geotechnical Investigation on Landslide in Nilgiris district of Tamilnadu" (Project sanction order NRDMS/11/2003/012 dt: 25/09/2014).

References

Anbazhagan P, Vinod JS, Sitharam TG (2009) Probabilistic seismic hazard analysis for Bangalore. Nat Hazards 48:145–166

Anbazhagan P, Parihar A, Rashmi HN (2012) Review of correlations between SPT N and shear modulus: a new correlation applicable to any region. Soil Dyn Earthq Eng 36:52–69

Ansal A (2004) Recent advances in earthquake geotechnical engineering and microzonation. Kluwer, New York

ArcGIS 9 Geographic information system (GIS) for working with maps and geographic information. ESRI

ASTM D2487-11 (2011) Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM International, PA, United States

Basu S, Nigam SC (1977) Seismic risk analysis of Indian peninsula. In: Proceedings of the 6th World conference on earthquake engineering, New Delhi, India, vol 1, pp 782–788

Bhandari RK (2006) The Indian landslide scenario, strategic issues and action points. In: India Disaster management Congress, New Delhi 29–30 November 2006, Session A2, Keynote address, pp 1–18

Bolt BA (1969) Duration of strong motion. In: Proceedings of the 4th national conference on earthquake engineering. Santiago, Chile, pp 37–50

Boominathan A, Dodagoudar GR, Suganthi A, Uma Maheswari R (2008) Seismic hazard assessment of Chennai city considering local site effects. J Earth Syst Sci 117:853–863

Budimir MEA, Atkinson PM, Lewis HG (2014) Earthquake-and-landslide events are associated with more fatalities than earthquakes alone. Nat Hazards 72:895–914

Chandrasekaran SS, Boominathan A, Dodagoudar GR (2013a) Dynamic response of laterally loaded pile groups in clay. J Earthq Eng 17(1):33–53

Chandrasekaran SS, Sayed Owaise R, Ashwin S, Jain Rayansh M, Prasanth S, Venugopalan RB (2013b) Investigation on infrastructural damages by rainfall-induced landslides during November 2009 in Nilgiris India. Nat Hazards 65(3):1535–1557

Chethanamba KR, Dodagoudar GR (2012) Probabilistic seismic hazard analysis using kernel density estimation technique for Chennai India. Georisk Assess Manag Risk Eng Syst Geohazards 6(1):1–15

Durukal E (2002) Critical evaluation of strong motion in Kocaeli and Duzce (Turkey) earthquakes. Soil Dyn Earthq Eng 22(7):589–609

Faccioli E (1991) Seismic amplification in the presence of geological and topographic irregularities. In: Proceedings of 2nd international conference on recent advances in geotechnical earthquake engineering, pp 1779–1797

Finn WD, Wu G, Thavaraj T (1997) Soil–pile–structure interactions. Seismic analysis and design for soil–pile–structure interactions. ASCE National convention, Minneapolis, pp 1–22

Ganapathy GP, Rajarathnam S (2010) Use of remote sensing and seismotectonic parameters to identify seismogenic sources of Tamilnadu state. Int J Appl Eng Res 1(1):59–76

Ganapathy GP, Rajawat AS (2015) Use of hazard and vulnerability maps for landslide planning scenarios: a case study of the Nilgiris, India. Nat Hazards. doi:10.1007/s11069-015-1587-z

Gazetas G, Mylonakis G (2005) Seismic soil–structure interaction: new evidence and emerging issues. In: Proceedings of international conference on geotechnical earthquake engineering and soil dynamics III, Berkley, USA, pp 1119–1173

Geli L, Bard PY, Jullien B (1988) The effect of topography on earthquake ground motion: a review and new results. Bull Seismol Soc Am 78:42–63

Houston SL, HoustonWN, Padilla JM (1987) Microcomputer-Aided evaluation of earthquake induced permanent slope displacement. Microcomputers in civil Engineering, pp 207–222

IMD (2012) Indian Meteorological Department, Ministry of earth sciences. http://www.imd.gov.in/section/seismo/dynamic/last-monthNov12.htm. Accessed 25 Dec 2012

IS 2131 (2002) Method for standard penetration test for soils. Bureau of Indian Standards, New Delhi

IS 1893–Part I (2002) Indian standard criteria for earthquake resistant design of structures part I general provisions and buildings. Bureau of Indian Standards, New Delhi

Jaiswal K, Sinha R (2007) Probabilistic seismic hazard estimation for peninsular India. Bull Seismol Soc Am 97(1):318–330

Jaiswal P, van Westen C, Jetten V (2011) Quantitative assessment of landslide hazard along transportation lines using historical records. Landslides 8(3):279–281

Jibson R (1987) Summary of research on the effects of topographic amplification of earthquake shaking on slope stability. Open-File Report 87-268, U.S. Geological Survey, Menlo Park, California.

Jibson RW (2011) Methods for assessing the stability of slopes during earthquakes—a retrospective. Eng Geol 122(1):43–50

Jibson RW, Michael JA (2009) Maps showing seismic landslide hazards in Anchorage, Alaska. U.S. Geological Survey, Scientific Investigations Map 3077 (scale 1:25000) pamphlet, pp 1–11

Joyner W, Boore D (1981) Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 imperial valley California Earthquake. Bull Seismol Soc Am 71:2011–2038

Kaila KL, Rao NM (1979) Seismic zoning maps of the Indian subcontinent. Geophys Res Bull, NGRI, Hyderabad 17:293–301

Kalyan Kumar G, Dodagoudar GR (2011) Seismic input motion for Kanchipuram, South India. Int J Earth Sci Eng 4:189–192

Kayal JR (2008) Microearthquake seismology and seismotectonics of south Asia. Capital Publishing Company, New Delhi

Khattri KN et al (1984) Seismic hazard map of India and adjoining areas. Tectonophysics 108:93–134

Kijko A, Graham G (1998) Parametric-historic procedure for probabilistic seismic hazard analysis: part I—estimation of maximum regional magnitude. Pure appl Geophys 152:413–442

Kramer SL (1996) Geotechnical earthquake engineering. Pearson Education Ptd, Ltd, New Delhi, India, (Reprinted 2003)

Krinitzsky EL (1995) Deterministic versus probabilistic seismic hazard analysis for critical structures. Int J Eng Geol 40:1–7

Lai CG, Menon A, Corigliano M, Ornthamarrath T, Sanchez HL, Dodagoudar GR (2009) Probabilistic seismic hazard assessment and stochastic site response analysis at the archaeological site of Kancheepuram in southern India. Research Report EUCENTRE 2009/01, IUSS Press, Pavia, ISBN 978-88-6198-037-2, pp 250

Lomnitz C (1970) The Peru earthquake of May 31, 1970. Bull Seismol Soc Am 60:1413–1416

Mandal P, Rastogi BK, Gupta Harsh K (2000) Recent Indian earthquakes. Curr Sci 79(9):1334–1346

Martha TR, Govindharaj KB, Kumar KV (2014) Damage and geological assessment of the 18 September 2011 Mw 6.9 earthquake in Sikkim, India using very high resolution satellite data, Geoscience Frontiers. doi:10.1016/j.gsf.2013.12.011
Menon A, Ornthammarath T, Corigliano M, Lai CG (2010) Probabilistic seismic hazard macrozonation of Tamil Nadu in southern India. Bull Seismol Soc Am 100(3):1320–1341
MoES (2009) Report on seismic microzonation of Bangalore. Urban Centre Seismology Division, Ministry of Earth Sciences, Government of India, New Delhi
NDMA (2010) Development of probabilistic seismic hazard map of India. Technical report of the working committee of experts constituted by the National Disaster Management Authority, Government of India, New Delhi
NDMG (2009) National disaster management guidelines—management of landslides and snow avalanches. A publication of the National Disaster Management Authority, Government of India, New Delhi
Parvez AI, Vaccari F, Panza GF (2003) A deterministic seismic hazard map of India and adjacent areas. Int J Geophys 155:489–508
Raghu Kanth STG, Iyengar RN (2006) Seismic hazard estimation for Mumbai city. Curr Sci 91(11):1486–1494
Rajakumar R, Sanjeevi S, Jayaseelan S, Isakkipandian G, Edwin M, Balaji P, Ehanthalingam G (2007) Landslide susceptibility mapping in a hilly terrain using remote sensing and GIS. J Indian Soc Remote Sens 35(1):31–42
Rodriguez CE, Bommer JJ, Chandler RJ (1999) Earthquake—induced landslides, 1980–1997. Soil Dyn Earthq Eng 18:325–346
Romeo R, Prestininzi A (2000) Probabilistic versus deterministic seismic hazard analysis: an integrated approach for siting problems. Soil Dyn Earthq Eng 20:75–84
Sanchez-Sesma FJ, Herrera I, Aviles J (1982) A boundary method for elastic wave diffraction: application to scattering of SH waves by topographic irregularities. Bull Seismol Soc Am 72:473–490
Schnabel PB (1973) Effects of Local Geology and Distance from Source on Earthquake Ground Motion, Ph.D. Thesis, University of California, Berkeley, California
Seed HB and Idriss IM (1970) Soil moduli and damping factors for dynamic response analysis. Report EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley
Seed HB, Murarka R, Lysmer J, Idriss IM (1976) Relationships of maximum acceleration, maximum velocity, distance from source and local site conditions for moderately strong earthquake. Bull Seismol Soc Am 66(4):1323–1342
SEISAT (2000) Seismotectonic atlas of India. Geological Survey of India, International Print-O-Pac Limited, B-202-206, Okhla Industrial Area, Phase-I, New Delhi
Sepulveda SA, Serey A, Pavez A, Barrientes S, Lara M (2008) Analysis of earthquake-induced landslides during the 2007 Aysen Fjord seismic swarm, Chilean Patagonia (45.5°S). International Geological Congress, No. 33. Proceedings, paper GHZ04203L
Seshagiri DN, Badrinarayanan S, Upendran R, Lakshmikantham CB, Srinivasan V (1982) The Nilgiri landslides—results of geotechnical and geological investigations. Miscellaneous Publication No. 57, Geological Survey of India, pp 1–41
SHAKE 2000 User manual: a computer program for the 1-D analysis of Geotechnical Earthquake Engineering Problems. GeoMotions LLC, Washington, U.S.A.
Singh SK, Pacheco JF, Bansal BK, Campos P, Dattatrayam RS, Suresh G (2004) A source study of the Bhuj, India, Earthquake of 26 January 2001 (Mw 7.6). Bull Seismol Soc Am 94:1195–1206
Sitharam TG, Anbazhagan P (2007) Seismic hazard analysis for the Bangalore region. Nat Hazards 40:261–278
Tsapanos TM, Koravos GC, Zygouri V, Tsapanos MT, Kortsari AN, Kijko A, Kalogirou EE (2011) Deterministic seismic hazard analysis for the city of Corinth-central Greece. J Balkan Geophys Soc 14(1):1–14
Trifunic MD, Hudson DE (1971) Analysis of the Pacoima Dam accelerogram—San Fernando, California, Earthquake of 1971. Bull Seismol Soc Am 61(5):1393–1411
Uma Maheswari R, Boominathan A, Dodagoudar GR (2010) Seismic Site classification and site period mapping for Chennai City using geophysical and geotechnical data. J Geophys 72:152–168