Earthquakes and Structures, *Vol. 10, No. 5 (2016) 1013-1032*
DOI: http://dx.doi.org/10.12989/eas.2016.10.5.1013

Site effects and associated structural damage analysis in Kathmandu Valley, Nepal

Dipendra Gautam[*1], Giovanni Forte[2a] and Hugo Rodrigues[3b]

[1]Structural and Earthquake Engineering Research Institute, Kathmandu, Nepal
[2]DICEA Department, Università degli Studi di Napoli Federico II, Naples, Italy
[3]RISCO, School of Technology and Management, Polytechnic Institute of Leiria, Leiria, Portugal

(Received November 20, 2015, Revised March 10, 2016, Accepted March 31, 2016)

Abstract. Several historical earthquakes demonstrated that local amplification and soil nonlinearity are responsible for the uneven damage pattern of the structures and lifelines. On April 25th 2015 the Mw7.8 Gorkha earthquake stroke Nepal and neighboring countries, and caused extensive damages throughout Kathmandu valley. In this paper, comparative studies between equivalent-linear and nonlinear seismic site response analyses in five affected strategic locations are performed in order to relate the soil behavior with the observed structural damage. The acceleration response spectra and soil amplification are compared in both approaches and found that the nonlinear analysis better represented the observed damage scenario. Higher values of peak ground acceleration (PGA) and higher spectral acceleration have characterized the intense damage in three study sites and the lower values have also shown agreement with less to insignificant damages in the other two sites. In equivalent linear analysis PGA varies between 0.29 to 0.47 g, meanwhile in case of nonlinear analysis it ranges from 0.17 to 0.46 g. It is verified from both analyses that the PGA map provided by the USGS for the southern part of Kathmandu valley is not properly representative, in contrary of the northern part. Similarly, the peak spectral amplification in case of equivalent linear analysis is estimated to be varying between 2.3 to 3.8, however in case of nonlinear analysis, the variation is observed in between 8.9 to 18.2. Both the equivalent linear and nonlinear analysis have depicted the soil fundamental period as 0.4 and 0.5 sec for the studied locations and subsequent analysis for seismic demands are correlated.

Keywords: site response analysis; structural damage; EERA; NERA; seismic demand; Gorkha Earthquake; Kathmandu valley

1. Introduction

On April 25th 2015 an Mw7.8 earthquake stroke Nepal and neighboring countries, Bangladesh, China and India. The affected region belongs to the Himalaya Arc, which historically originated very large earthquakes with a moment magnitude higher than Mw7.5.The epicenter was located

*Corresponding author, Researcher, E-mail: strdyn@yahoo.com
[a]Ph. D., E-mail: giovanni.forte@unina.it
[b]Ph. D., E-mail: hugo.f.rodrigues@ipleiria.pt

http://www.techno-press.com/journals/eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

near the village of Gorkha, about 77 km from Kathmandu, the capital city of Nepal, which is home to nearly 1.5 million inhabitants. The focal depth of the earthquake was approximately 10-15 km. This earthquake is the most powerful earthquakes to strike Nepal since the 1934 Nepal-Bihar earthquake (M_w8.1). It affected both natural and building environments, i.e., landslides and avalanches developed in mountainous areas, while soil liquefaction and amplification of ground motion occurred in the soft soils in areas of plain and within Kathmandu valley. The latter was the main cause of the collapse or heavy damage to residential buildings, historical and monumental constructions as well as the heritages.

Earthquakes damage is highly increased by ground effects, as landslides and liquefaction (Santucci de Magistris *et al*. 2014, Forte *et al*. 2015, Forte and Santucci de Magistris 2015), as well as to the seismic site response analysis (Santucci de Magistris *et al*. 2014).

Previous studies, which dealt with seismic site response analyses in Kathmandu valley mainly focused on equivalent linear approaches (e.g., Maskey and Dutta 2004, Paudyal *et al*. 2012, Chamlagain and Gautam 2015a, b, Gautam and Chamlagain 2015a, 2016a, 2016b), hence, in this paper, a comparative study of equivalent linear and nonlinear seismic site response analysis is performed, in order to delineate the pattern of spectral acceleration and spectral amplification. The variations in surface motion parameters from both approaches have been discussed for five ideal locations of Kathmandu valley, which are world heritage sites, administrative centers or commercial centers.

2. Geological and seismotectonic setting

2.1 Geology of Kathmandu valley

Kathmandu valley lies in an intermountain basin developed in a large syncline between the Sheopuri Lekh and the Mahabharat Range of the Lesser Himalaya region in Nepal. The basement is constituted by slates, phyllites, siltstones, sandstones and calcareous rocks, with a Precambrian to Devonian age, while the filling is made of fluvio-lacustrine unconsolidated sediments of Pliocene to Quaternary age (Fig. 1) with varying thickness (Yoshida and Igarashi 1984). Katel *et al*. (1996) estimated depth of sediments to be 550 m, while gravity measurements suggested the maximum thickness of soft soil deposits to be upto 650 m (Moribayashi and Maruo 1980).

Basement rocks constitute the Kathmandu Complex (Stocklin and Bhattarai 1977), which is composed of Precambrian Bhimphedi Group, consisting of relatively high-grade meta-sediments and the Phulchauki Group of un-metamorphic or weakly metamorphosed sediments containing fossils of early-Middle Palaeozoic age. These two are possibly separated by a slight unconformity. Associated with the meta-sediments, the Kathmandu Complex also contains gneisses and granites. The basin-fill sediments are broadly divided into three sedimentary facies: the fluvio-deltaic facies from north to center, fluvio-lacustrine facies from south to center, and gravelly fan and fluvial facies from southern margin of the basin.

The southern part of the valley consists of hill terraces formed during late Pliocene to middle Pleistocene (Yoshida and Igarashi 1984). It is formed by the Tarebhir Formation, Lukundol Formation, and Itaiti Formation (Sakai 2001). The central part of the valley consists of Bagmati Formation, Kalimati Formation, and Patan Formation. The Bagmati River Formation was active before the lake formation and is responsible for deposition of sediments in most part of the valley. The black clayey central portion is called the Kalimati Formation, with dark grey carbonaceous

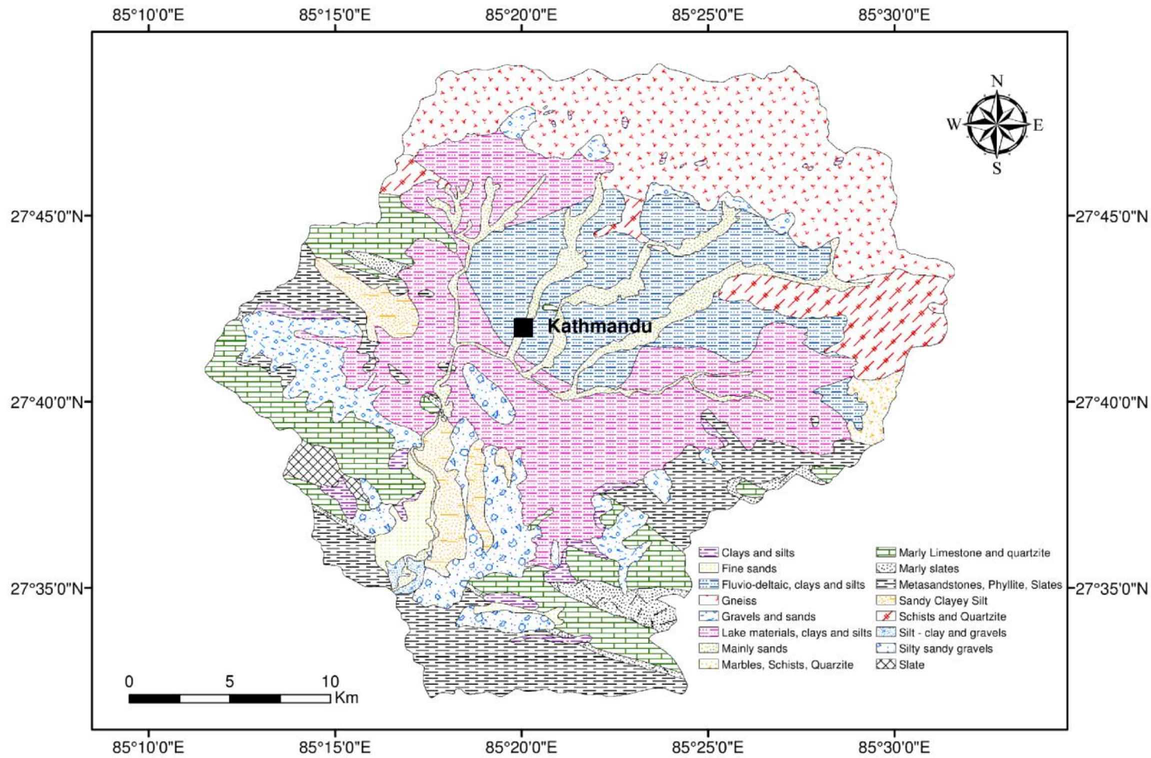

Fig. 1 Simplified geological map of the Kathmandu valley

and diatomaceous beds of the open lacustrine facies. The Patan Formation is distributed in and around Kathmandu and Patan city, consisting of fine to medium sand and silt intercalated with clay and fine gravels in some places. The northern and northeastern part of Kathmandu valley consists of fluvio-deltaic or fluvio-lacustrine origin, mostly sandy facies called Gokarna and Thimi Formation (Yoshida and Igarashi 1984, Sakai 2001). The Kathmandu valley rocks are intersected by a number of faults systems. The Chandragiri fault and the Chovar fault acting on southern part of Kathmandu valley are considered to be active faults cutting the colluvial slopes and the terraces of the late Pleistocene age (Sakai 2001).

2.2 Seismotectonic setting

Seismic events occurred in historical times (1255, 1408, 1681, 1803, 1810, 1866, 1988, 1934) devastated the villages within Kathmandu valley (Chitrakar and Pandey 1986, Gupta 1988, Bilham *et al*. 1995, Pandey *et al*. 1995). These events had spectacular evidences in terms of damages, the same devastation was observed after 2015 Gorkha earthquake as well.

The micro-seismicity in Nepal has depicted three different clusters (Pandey *et al*. 1999). The eastern Nepal cluster is situated between 86.5°E and 88.5°E, the central Nepal cluster is placed in between 82.5°E and 86.5°E and that for the western Nepal; it lies between 80.5°E and 82.5°E. The general trend reflects the narrow belt of predominantly moderate-sized earthquakes below the Lesser Himalaya and just south of the Higher Himalayan Front. The basal decollement beneath the

Table 1 Summary of the main Himalayan earthquakes occurred in the last century

Year	**Earthquake**	**Magnitude M_w**
1897	Shillong	8.1
1905	Kangra	7.8
1934	Bihar-Nepal	8.1
1950	Assam	8.7
1988	Udaypur	6.5
1991	Uttarkashi	6.9
2005	Kashmir	6.2
2011	Sikkim-Nepal	6.9
2015	Gorkha	7.8

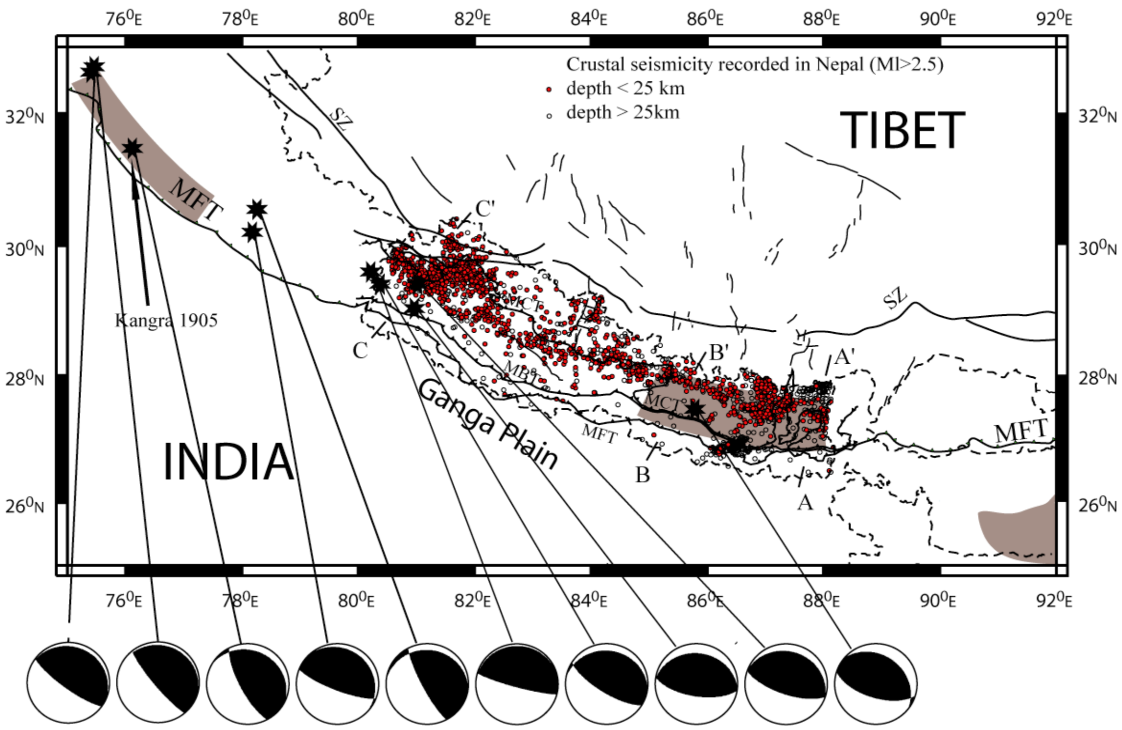

Fig. 2 Seismicity in the Himalayas of Nepal (after Jouanne *et al*. 2004);the intense microseismicity (monitored between 1985-1998) drawn with small grey circles, tend to cluster south of the Higher Himalayas (Pandey *et al*. 1999) at a mid-crustal level. Stars represent medium size earthquake

Siwalik and Lower Himalaya are the most common hubs for every great Himalayan earthquake with rupture length of several hundred kilometers as shown for the events listed in Table 1 (Bilham 1995, Seeber and Armbruster 1981, USGS 2011).

The focal depth of these earthquakes has been found to be varied in a range of 10-20 km (Fig. 2). While considering the events after 1800, the estimated minimum slip deficit for around 60% of the arc is 4 m, which may lead to several major earthquakes in this region, with possibility of 10 m slip (Bilham *et al*. 1997). At this juncture, it is believed that the central seismic gap (the area between Dehra Dun and Kathmandu) of the western Nepal has not been ruptured since 1505, which indicates 9m of accumulated potential slip, with assumption that the fault is fully locked, that might cause a major earthquake $M_w > 8$ (Bilham and Ambraseys 2004).

3. Site response analyses

3.1 An overview

Evaluation of ground response during earthquakes is a key topic in geotechnical earthquake engineering. The impact of local geologic soil conditions on the intensity of the ground shaking and associated damages is widely recognized (Aki and Larner 1970, Aki 1993, Psarropoulos *et al*. 1999, Semblat *et al*. 2004, Psarropoulos *et al*. 2007, Lanzo *et al*. 2011, Chamlagain *et al*. 2013, Chamlagain and Gautam 2015). Local soil conditions significantly affect the characteristics of strong ground motion in terms of amplitude, frequency content and duration. The quantitative depiction of these parameters is governed by the geometry and material properties of the subsurface materials, site topography and characteristics of the input motion. During 1906 San Francisco, 1923 Kanto, 1934 Bihar-Nepal, 1964 Nigata, 1964 San Francisco, 1980 Irpina, 1985 Mexico City, 1989 Loma Prieta, 1995 Kobe, 2009 L’Aquilla and 2015 Gorkha earthquakes, seismic site effects have been more pronounced in terms of localized damage to infrastructures. Though, seismic site effects is being continuously dealt since 1920s, with the increased trend of recording the strong ground motion, seismic site effects have been more incorporated after 1970s. With the use of strong ground motion data various methods have been developed to depict the seismic site effects after 1970,like Soil-to-rock spectral ratios (e.g., Borecherdt 1970), generalized inversion (e.g., Iwata and Irikura 1988, Boatwright 1991) and horizontal-to-vertical spectral ratios (e.g., Joyner and Chen 1975, Lam et al. 1978, Nakamura 1988, Lermo and Chavez-Garcia 1993, Field and Jacob 1995, Yamazaki and Ansary 1993, Bardet *et al*. 2000, Bardet and Tobita 2001).

In order to quantify the dynamic response of soil, linear, equivalent linear and fully nonlinear approaches are practiced; several stress-strain models have been developed in order to model the soil behavior through experimental modeling (e.g., Seed and Idriss 1970, Hardin and Dmevich 1972, Vucetic and Dobry 1991). Previous studies performed by Yoshida (1994), Huang *et al*. (2001) and Yoshida and Iai (1998) have shown the larger peak spectral acceleration because of the method used for calculation implements high frequency range (Arslan and Siyahi 2006). Moreover, the equivalent-linear analysis has been found to be over-estimating the amplification pattern in terms of absolute amplification level (Hosseni and Pajouh 2010). The comparative analysis carried out by Kaklamnous *et al*. (2013) and Kim *et al*. (2013) reflects the adequacy of equivalent linear method for short period and for longer period; both methods designate the same acceleration. Bolisetti *et al*. (2014) performed comparative analysis of equivalent linear and nonlinear site response analysis and found that the results from equivalent-linear method were unable to reproduce the high frequency acceleration response which ultimately led to almost constant spectral acceleration in the short period range.

Nonlinear site response analysis has been gaining popularity in recent years as most of the geotechnical earthquake engineers agreed on soil nonlinearity from various laboratory investigations. Under the cyclic loading the stress-strain relationship is truly nonlinear and hysteretic for the strain larger than 10^{-4} (Erdik 1987). The field observations from 1989 Loma Prieta and 1994 Northridge California earthquakes have affirmed the presence of soil nonlinearity too (Safak 2001). It is obvious that, soil imposes nonlinearity even in small strain; hence nonlinear site response analysis is gaining momentum in recent dates.

3.2 The comparative analysis between EERA and NERA

Equivalent Linear Earthquake Site Response Analysis (EERA) and Nonlinear Earthquake Response Analysis (NERA) are adopted for analysis of ground response. EERA (Bardet *et al*. 2000) is a modern implementation of established concepts of equivalent linear earthquake site response analysis. It has got advantage in dynamic array dimensioning and matrix operations in FORTRAN 90. EERA overcomes the limitations of SHAKE 91 and due to user friendliness is gaining more attention in estimation of seismic site effects. For equivalent linear analysis, dynamic soil properties estimated by Seed andIdriss (1970) are used. In 2001, the advancement of EERA was performed as NERA (Bardet and Tobita 2001). While incorporating and exact account of soil behavior, nonlinear analysis is done. Nonlinear site response analysis is based upon the material model developed by Iwan (1967) and Mroz (1967). Conversely, for nonlinear analysis, dynamic properties of soils predicted by Seed and Sun (1989) are adopted.

The seismic response analyses with both approaches were performed in five chosen sites,

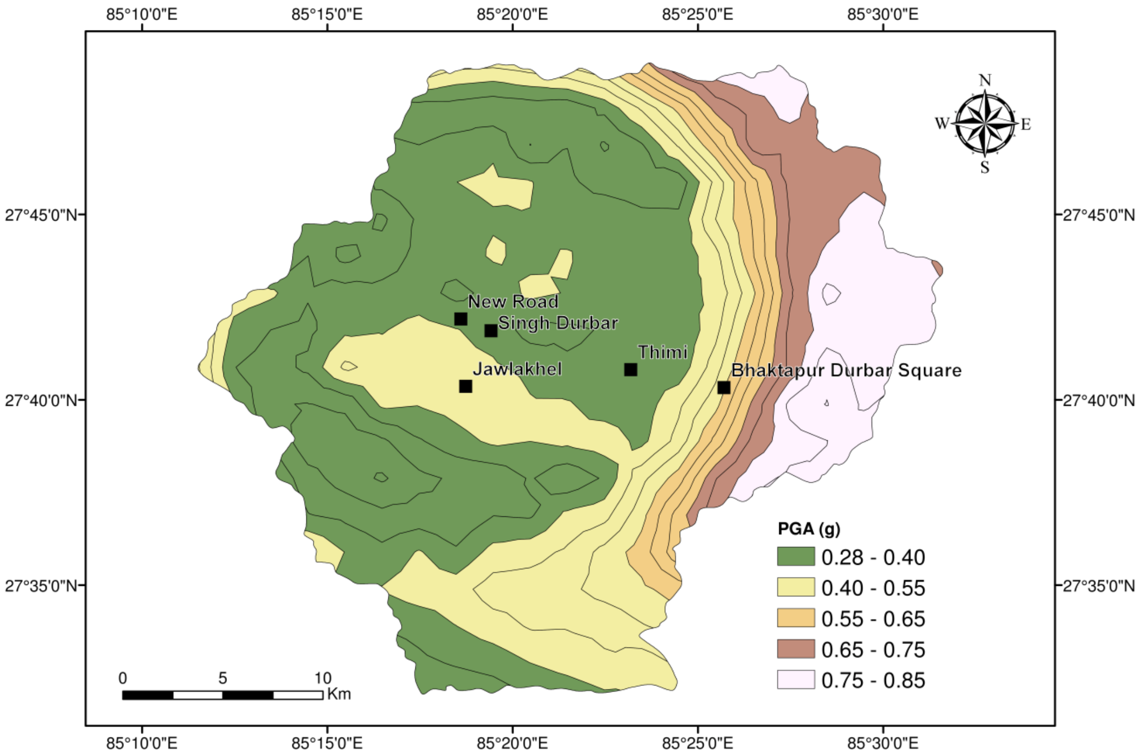

Fig. 3 PGA map derived by USGS shakemap and location of the studied sites

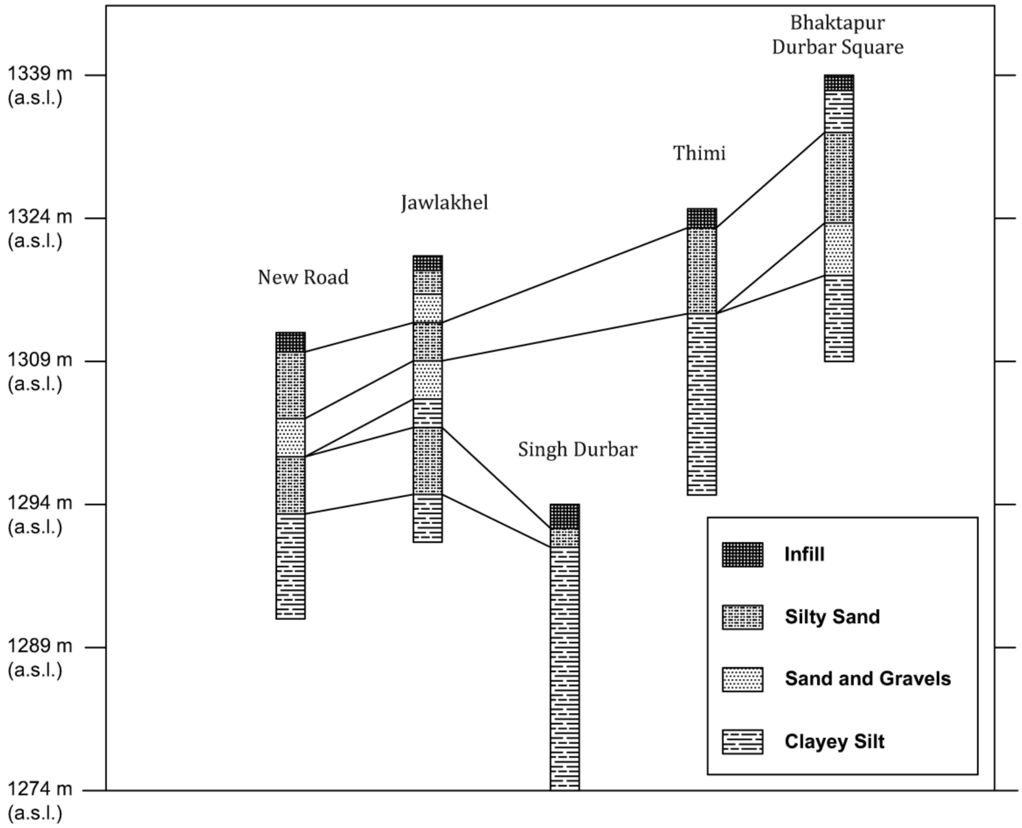

Fig. 4 Stratigraphic logs of the five analyzed sites

which constitute world heritage sites, administrative centers or commercial centers. Furthermore, for those five sites a database of measured shear wave velocities by PS logging is available. The sites location is shown in Fig. 3 together with the peak ground acceleration (PGA) distribution derived by USGS Shakemap. Singh Durbar is the major administrative center of Nepal, Bhaktapur Durbar Square and Kathmandu Durbar Square (New Road) are world heritage sites, Jawlakhel is the major commercial and residential center in Kathmandu valley and Thimi is a relevant historic settlement of Nepal. According to the PGA map of Fig. 3, three sites (New Road, Singh Durbar and Thimi) fall in the range of 0.28-0.4 g and the other two (Jawlakhel and Bhaktapur Durbar Square) experienced higher accelerations between 0.4 and 0.55 g.

As concerns, the stratigraphical setting for the five sites in Kathmandu valley, the logs are sketched in Fig. 4. All of them show a stratigraphic succession mainly composed of interbedding of fine and very fines soils, constituted by silty sands and clayey silts, Thimi and Singh Durbar in particular. In the others it is relevant to highlight the presence of a layer of sands 4-5 m thick.

The shear wave velocities and the geotechnical properties were recorded during the study carried out by Japan International Cooperation Agency (JICA) on earthquake disaster mitigation (JICA 2002). In Fig. 5 the shear wave profiles derived by down-hole investigations are also reported. The materials are very soft as the V_S values vary between 150 to 400 m/s, with frequent inversion of velocity with depth.

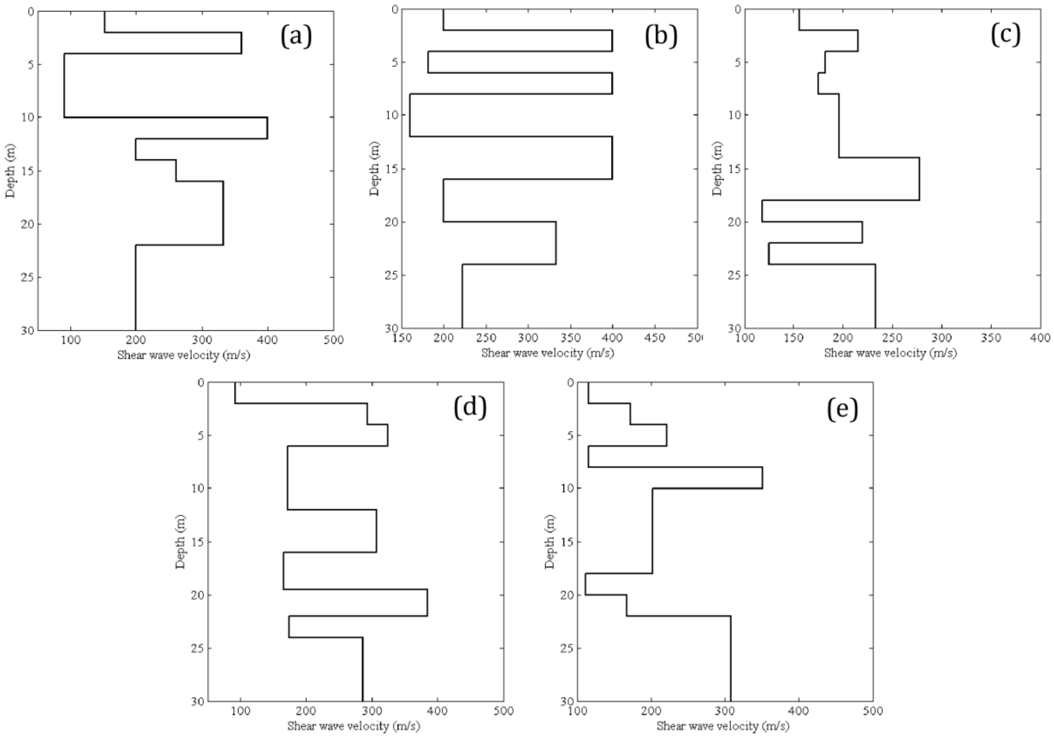

Fig. 5 Shear wave profiles of the study sites (a) Bhaktapur Durbar Sqaure (b) Jawlakhel (c) New Road (d) Singh Durbar and (e) Thimi

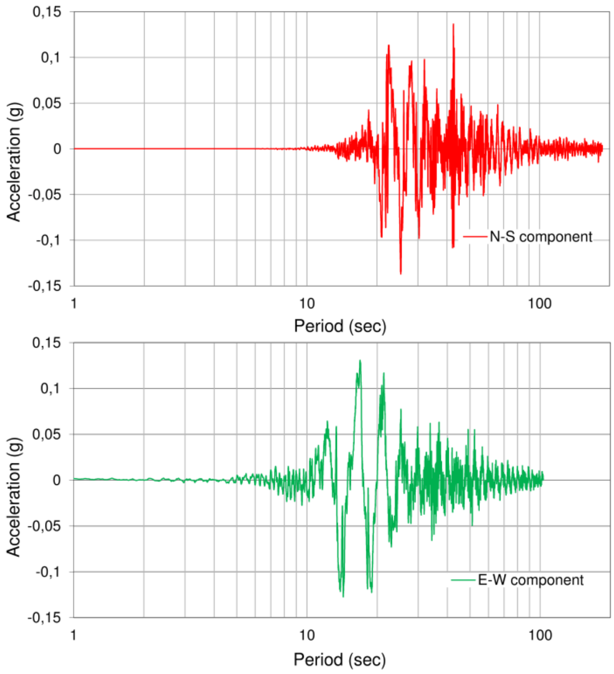

Fig. 6 Acceleration time history of Gorkha earthquake

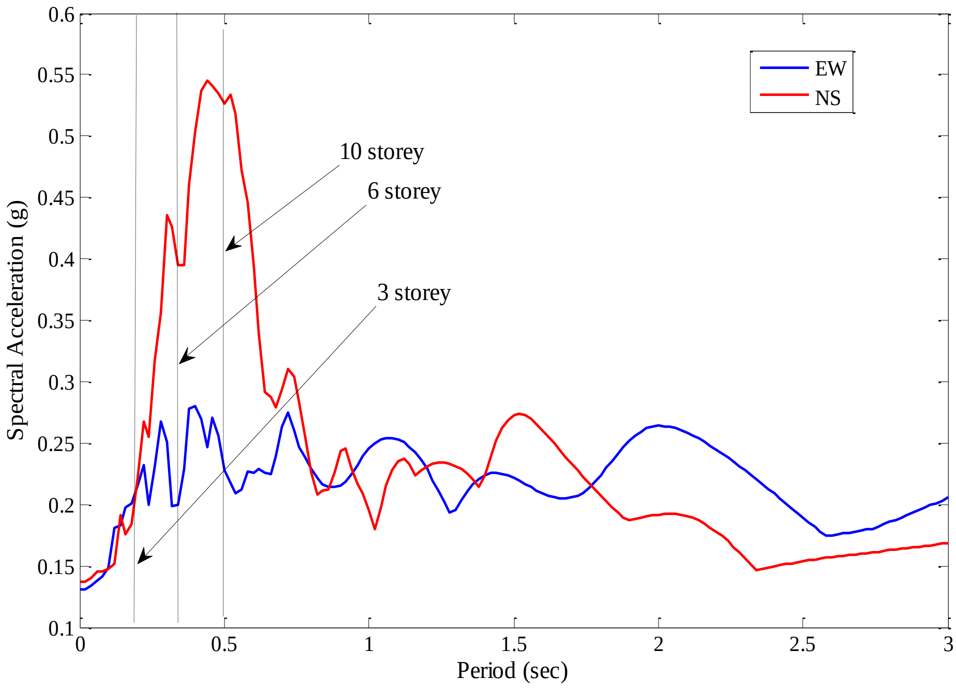

Fig. 7 Acceleration response spectra of input motion

The analyses for both equivalent linear and nonlinear platform were performed adopting as seismic input, the ground motion recorded on the rock site in the vicinity of Kathmandu valley during the main shock event of 25th April, 2015. The accelerometer records depict a PGA of 0.13 g at 16.9 sec for EW component and same value of 0.13 g at 25.3 sec for NS component (Fig. 6). In order to enhance the reliability of analysis, the input PGA is scaled into 0.25 g for input acceleration time history because in some sites the unpublished database have shown the PGA range upto 0.25 g. For both equivalent-linear and nonlinear analyses, the NS component of time history is chosen and inputted on the engineering bedrock level and the corresponding ground motion parameters on surface are calculated for all sites. However, separate material curves are adopted to represent the equivalent-linear and fully nonlinear soil behaviour. In order to obtain a more comprehensive comparison of the earthquake, the 5% damped response spectra are formulated for the EW and NS components (Fig. 7) and hence the numbers of storeys in structures are correlated in order of seismic demand.

4. Discussion of the results

Table 2 reports a summary of the results for the several parameters evaluated. The peak ground accelerations for the scaled PGA input of 0.25 g for 2015 Gorkha earthquake main shock are estimated to be 0.47 g, 0.29 g, 0.31 g, 0.29 g and 0.29 g respectively for Bhaktapur Durbar Square, Jawlakhel, New Road, Singh Durbar and Thimi in equivalent linear platform. Similarly the corresponding peak spectral accelerations are obtained to be 2.08 g, 1.11 g, 1.30 g, 1.02 g and 1.20

g respectively as presented in Table 2. The spectral amplification factors which indicate the increment in ground motion intensity due to dynamic response of local soil layers and given by the ratio of spectral acceleration in soil to spectral acceleration in rock are estimated for each study sites. The spectral amplification factors for Bhaktapur Durbar Square, Jawlakhel, New Road, Singh Durbar and Thimi are estimated to be 2.3, 2.9, 2.5, 3.8 and 2.6 respectively in the frequency range of 0.4 to 0.8 Hz. The soil fundamental period for Bhaktapur, New Road, Singh Durbar and Thimi is estimated as 0.5 sec; however, the Jawlakhel site has the value of soil fundamental period of 0.4 sec. Conversely, in case of nonlinear analysis, PGA for Bhaktapur Durbar Square, Jawlakhel, New Road, Singh Durbar and Thimi is obtained as 0.46 g, 0.17 g, 0.38 g, 0.32 g and 0.34 g respectively having corresponding peak spectral accelerations as 1.65 g, 0.48 g, 1.42 g, 0.97 g and 1.04 g. On the other hand, the spectral amplification factor is obtained as 18.2, 8.9, 11.4, 9.7 and 17.7 respectively for Bhaktapur Durbar Square, Jawlakhel, New Road, Singh Durbar and Thimi respectively in the frequency range of 15.3 to 16.5 Hz. The soil fundamental period is estimated to be similar in case of nonlinear analysis as that of equivalent linear analysis. The comparative response spectra for both equivalent linear and nonlinear analysis along with the response spectra of input motion are presented in Fig. 8. The obtained results are closely correlated with the PGA map derived by USGS. As the map depicts the variation of PGA from 0.28 to 0.85 g, three analyzed sites (New Road, Singh Durbar and Thimi) are in the range of value 0.28-0.40 g similar to the USGS PGA map in both equivalent linear and nonlinear analysis. The Bhaktapur Durbar Square site also correlates with the USGS PGA map; however the Jawlakhel site has shown strong disagreement, which designates Jawlakhel in the range of 0.40 g to 0.55 g range. The

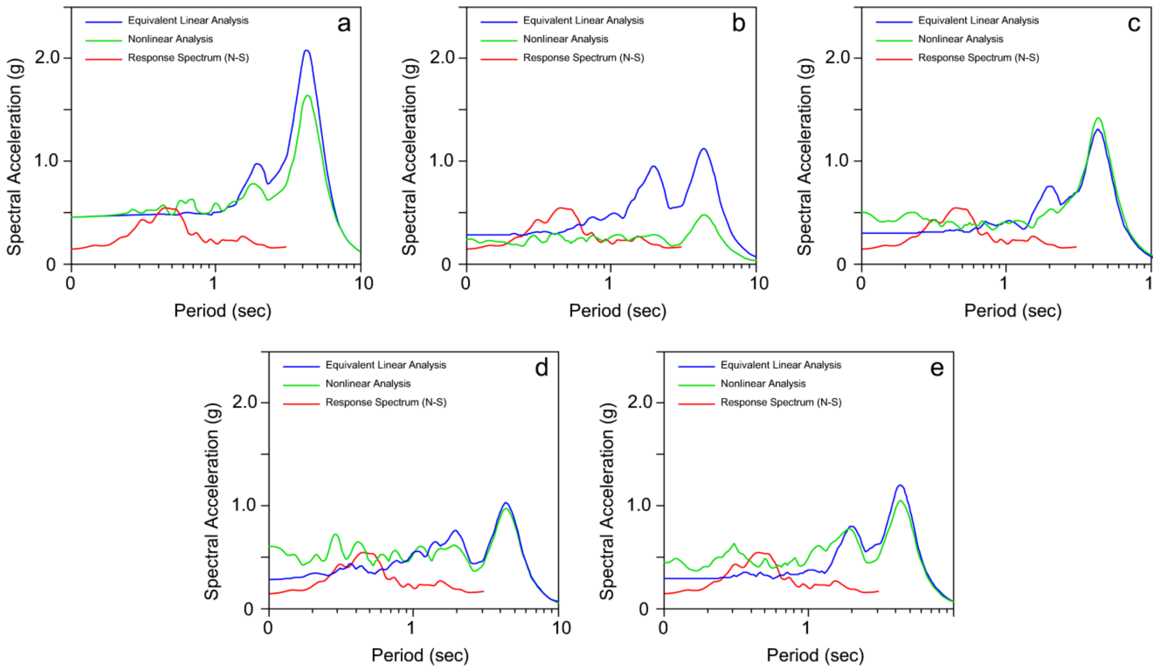

Fig. 8 Comparative response spectra for (a) Bhaktapur Durbar Square (b) Jawlakhel (c) New Road (d) Singh Durbar and (e) Thimi

Table 2 Summary of results for equivalent linear and nonlinear analysis along with the number of stories calculated for seismic demand analysis of multi-storied RC buildings

Site	Equivalent Linear Analysis							Nonlinear Analysis						
	PGA (g)	PSA (g)	Amplification factor	Frequency of maximum amplification (Hz)	Soil Fundamental Period (sec)	No. of stories in terms of seismic demand		PGA (g)	Peak Spectral Acceleration (g)	Amplification factor	Frequency of maximum amplification (Hz)	Soil Fundamental Period (sec)	No. of stories in terms of seismic demand	
						NEHRP	Enamoto *et al.*						NEHRP	Enamoto *et al.*
Bhaktapur Durbar Square	0.47	2.08	2.3	0.4	0.5	5	10	0.46	1.65	18.2	15.6	0.5	5	10
Jawlakhel	0.29	1.11	2.9	0.6	0.4	4	8	0.17	0.48	8.9	10.7	0.4	4	8
New Road	0.31	1.30	2.5	0.4	0.5	5	10	0.38	1.42	11.4	15.3	0.5	5	10
Singh Durbar	0.29	1.02	3.8	0.8	0.5	5	10	0.32	0.97	9.7	15.9	0.5	5	10
Thimi	0.29	1.20	2.6	0.4	0.5	5	10	0.34	1.04	17.7	16.5	0.5	5	10

obtained PGA in Jawlakhel in both equivalent linear and nonlinear analysis is lower than the inferior boundary of USGS PGA map.

In order to outline the vibration resonance between soil and structures, the soil fundamental period is analyzed in relation to the structural time period. Several researchers have proposed various expressions to estimate the first natural period of buildings based on typology and region. Based on proposal of Enomoto *et al*. (1998) with expression 1, natural frequency of the RC buildings in study region is calculated correlating with the soil fundamental period

$$T = 0.05 \times N \tag{1}$$

where T is the period in seconds and N is the number of stories

Similarly, the NEHRP (1994) provision for estimating the building period estimation can be expressed as

$$T = 0.1 \times N \tag{2}$$

The results obtained are plotted in Fig. 7. The response spectrum was obtained from the acceleration records. The predicted natural frequencies of RC buildings, as represented in the figure, indicates a concentration of the larger seismic demand for buildings with more than 6 storeys. This information may be correlated with the low damage observed in low rise RC fully infilled buildings, however in RC buildings with open ground storeys with higher time periods were having higher levels of damage, associated also with the vertical irregularities.

As the soil fundamental period is estimated to be 0.4 sec for Jawlakhel and 0.5 sec for all other four sites, the seismic demand analysis for specified storied RC structures is performed and in case of Enamoto *et al*. (1998) formulation, buildings of 9.5 stories in Jawlakhel and 12 storied buildings in all other four sites are requiring larger seismic demand. The variation in soil fundamental period estimated in analyses and the predominant period observed in Fig. 8 correlates with the possibility of nonlinear soil characteristics. The material curves in this study are not derived from in-situ field tests, however adopted from standard material curves derived for similar soil conditions, thus the discrepancy in estimated soil fundamental period and the observed predominant period in Fig. 8 is due to the effect of nonlinearity and material properties. As per the present trend of construction, 9.5 storied RC structures in Jawlakhel and 12 storied constructions in all other four sites do not exist. Meanwhile, NEHRP provision seems to be realistic for seismic demand of specified storied structures. For Jawlakhel, 4 storied structures demand higher seismic demand and for all other sites 5 storied structures are requiring higher seismic considerations as depicted in Table 1. The RC damage pattern in Kathmandu valley has shown strong correlation with the estimated seismic demand as majority of prevalent structures in Kathmandu valley are of 2-6 storied with exception to a few high rise structures (Chaulagain *et al*. 2014, Gautam *et al*. 2015, Gautam *et al*. 2016). So, it is obvious that the prevalent structures in Kathmandu valley are facing higher vulnerability in terms of vibration resonance during earthquakes. Majority of the damaged structures in northeastern part of Kathmandu valley were 4-5 storied (Fig. 9) and notably the soil characteristics of the damaged area show close acquaintance with the soil type of Bhaktapur Durbar Square and Thimi. As depicted by Fig. 9, the five storied structure with almost similar construction technology and age is collapsed however higher storied structures are intact.

The equivalent linear analysis has given higher acceleration values and lower amplification as compared to the nonlinear analysis. In recent contribution of Chamlagain and Gautam (2015b) several sites within Kathmandu metropolitan city have been depicted to be de-amplified during 2015 Gorkha earthquake, however the shear wave velocities for those analyzed sites were not directly measured rather the correlation developed by Gautam *et al*. (2016) was used. In this contribution, the observed damages and soil behavior during 2015 Gorkha earthquake are more representatively correlated with the nonlinear analysis. As soil behaves like a nonlinear material even in small strains, it is rational to carry out the nonlinear analysis. The variation of results is widely accompanied by inter-bedded soil materials and their types, the amplification and spectral acceleration values are found to be scattered as well. All of the five analysis sites lie in soft soil deposits of Kathmandu valley so relatively higher values of spectral acceleration and amplification factors are obtained in case of nonlinear analysis.

More precisely, those sites with dominance of silt and clay are found to be observing larger

Fig. 9 A damaged five storied building in northeastern part of Kathmandu valley

amplification in both equivalent linear and nonlinear analysis showing very large amplification during nonlinear analysis. The nonlinear analysis has depicted higher values of amplification in allocations. During M_W7.8 Gorkha earthquake, widespread damage in the unreinforced masonry structures and localized damages were observed in RC structures across Kathmandu valley. Bhaktapur Durbar square is severely damaged during Gorkha earthquake (Fig. 10) which is consistent with the higher PGA and spectral amplification in study. The structural damages in Thimi are also comparable to Bhaktapur Durbar Square (Fig. 11); this is well reinforced by the results of analysis in terms of higher PGA and spectral amplification. Both Bhaktapur Durbar Square and Thimi are hillocks situated in higher elevation than the surrounding areas, so relatively higher amplification was expected. This is more represented by nonlinear analysis. Furthermore, some taller heritage and monumental collapses were observed in New Road (Fig. 12). The damage in New Road is observed as lesser than Bhaktapur Durbar Square and Thimi however relatively higher than Singh Durbar and Jawlakhel. This is evidently supported by the nonlinear analysis rather than the equivalent linear one. In Singh Durbar, some tensile as well as shear cracks were observed in the massive monuments of early 20th century (Fig. 13). The cracks were more prevalent in re-entrant corners, and the structural damages were not serious too. Jawlakhel area was least affected during 2015 Gorkha earthquake, except few shear and tensile cracks and some parapet wall failure, there was no significant damage in structures in Jawlakhel area (Fig. 14). All these damage scenarios are well supported by nonlinear analysis. However, the equivalent linear analysis doesn't correlate properly with the observed damages during Gorkha earthquake. Besides, the damages were also influenced by the local construction technology, material deficiencies and topographical conditions.

The wider variation of peak spectral acceleration and amplification within the study areas highlight the necessity of a microzonation plan for Kathmandu valley. Paudyal *et al*. (2012) estimated the variation of dominant period in the range of 0.11-2.05 sec and Chamlagain and

Fig. 10 Damage in RC strutcure and a completely collapsed neighborhood in Bhaktapur

Fig. 11 Damage in Thimi

Fig. 12 Damage in New Road in heritage and monuments

Gautam (2015b) depicted the variation of dominant period to be 0.3-0.7 sec; meanwhile this study estimates the range 0.4-0.5 sec which suggests more close range of soil predominant period. In addition to this, The localized damage trend during 2015 Gorkha earthquake has suggested the larger variation in local soil response, though due to lack of dynamic soil properties and proper geotechnical investigations, representative models are not developed for Kathmandu valley. This preliminary attempt suggests the possibility of intense damage within Kathmandu valley if strong earthquakes near Kathmandu occur in near future.

Fig. 13 Partial damage in Singh Durbar

Fig. 14 Toppled parapet wall of RC building and out of plane failure of masonry structture in Jawlakhel

The larger seismic demand depiction in the study area is significant due to limited horizontal expansion remaining in Kathmandu valley and inevitable vertical expansion of structures. Studied sites comprise majority of structures having from 4 to 5 stories, however these structures are not accounted with proper seismic design and never considered for enhanced seismic demand anywhere. Thus, seismic demand in the range of 4 to 5 stories is vital to ensure the seismic safety of structures in future events.

5. Conclusions

The April 25th 2015 Gorkha earthquake affected Nepal both in natural and building environments, i.e., landslides and avalanches developed in mountainous areas, while soil liquefaction and amplification of ground motion occurred in the soft soils in areas of plain. The latter was the main cause of the collapse or heavy damage to buildings, some of them constituted by historic buildings and temples. This paper disseminates a comparative study of equivalent linear and nonlinear seismic site response analysis for five strategic locations of Kathmandu valley, which were badly affected and depicts that the nonlinear site response analysis is more representative than the equivalent linear analysis. This fact strongly undergirds the nonlinear soil behavior within the Kathmandu valley soft soil deposits.

The results showed that soil nonlinearity has a significant role in the damage pattern as retrieved in the post-earthquake surveys. In particular, higher soil amplification and relatively higher PGA values in analyzed sites coincided with the wider and worse damage scenario. This inference is well supported by the nonlinear analysis. Calculation of acceleration in high frequency range in case of equivalent linear analysis usually overestimates the spectral acceleration and degrades the value of amplification, equivalent linear analysis is found to be less representative for alluvial soft soil deposits like Kathmandu valley. Beside this, it is observed that the estimated PGA range predicted by USGS for southern part of Kathmandu valley is not representative enough, because the damage scenario of Jawlakhel reflects discrepancy with predicted PGA range. Although, the structural composition and construction technology between Jawlakhel and New Road weren’t significantly different, damage was more intense in New Road. Except Jawlakhel, all other analyzed sites have shown agreement with USGS PGA distribution map. In this study, the PGA range for five study sites is estimated to be 0.29-0.47 g in case of equivalent linear analysis and 0.17-0.46 g for nonlinear analysis. Apart from this, the spectral amplifications are predicted in the range of 2.3 to 3.8 in case of equivalent linear analysis and 8.9-18.2 for nonlinear analysis. The soil fundamental period in both approaches is estimated to be 0.4-0.5 sec for all sites.

The traditional masonry structures in Kathmandu valley experienced the worst damage, while the damage in reinforced concrete (RC) structures resulted relatively low and localized. The biggest of the damage was found at Bhaktapur Durbar Square and Thimi due to the coexistence of soft sediments and very old traditional masonry structures.

The wider variation of peak spectral acceleration and amplification within Kathmandu valley is mainly due to soft soil layers of lacustrine origin, which combined with a repeated history of frequent earthquake, this highlight the high seismic risk present in the area, whereas Kathmandu valley still lacks the microzonation plan. The rebuilding effort should consider with the seismic resistant design and associated connections in vibration resonance accounting larger seismic demand of 4 to 5 storied structures as per NEHRP provisions. Future earthquakes with higher PGA and amplification will be more detrimental in terms of damage surpassing the examples from the

2015 Gorkha earthquake, however more localized and site specific design spectra as per the local soil conditions may be instrumental in assuring seismic safety and better performance of structures. The ground motion parameters have shown relatively higher values with significant difference within small spatial variation, so localized microzonation and site specific studies are urgently needed for assuring performance based design of structures and associated seismic risk reduction.

Acknowledgements

Authors are grateful to Prof. Filippo Santucci de Magistris (University of Molise, Campobasso, Italy) for his remarks to improve the text quality and interpretation of results.

References

Aki, K. (1993), "Local site effects on weak and strong ground motion", *Tectonophysics*, **218**(1), 93-111.

Aki, K. and Larner, K.L. (1970), "Surface motion of a layered medium having an irregular interface due to incident plane SH waves", *J. Geophys. Res.*, **75**(5), 933-954.

Arslan, H. and Siyahi, B. (2006), "A comparative study on linear and nonlinear site response analysis", *Environ. Geol*., **50**(8), 1193-1240.

Bardet, J.P. and Tobita, T. (2001), *NERA: A Computer Program for Nonlinear Earthquake Site Response Analyses of Layered Soil Deposits*, Department of Civil Engineering, University of Southern California, Los Angeles, CA.

Bardet, J.P., Ichii, K. and Lin, C.H. (2000), *EERA: A Computer Program for Equivalent-Linear Earthquake Site Response Analyses of Layered Soil Deposits*, Department of Civil Engineering, University of Southern California, Los Angeles, CA.

Bilham, R. (1995), "Location and magnitude of the 1833 Nepal earthquake and its relations to the rupture zones of contiguous great Himalayan earthquakes", *Curr. Sci*., **69**(2), 101-128.

Bilham, R. and Ambraseys, N. (2004), "Apparent Himalayan slip deficit from the summation of seismic moments for Himalayan earthquakes", *Curr. Sci.*, 1500-2000.

Bilham, R., Larson, K.M., Freymueller, J. and PI members (1997), "GPS measurements of present day convergence across the Himalaya", *Nature*, **386**(6620), 61-64.

Boatwright, J., Fletcher, J.B. and Fumal, T.E. (1991), "A general inversion scheme for source, site, and propagation characteristics using multiply recorded sets of moderate-sized earthquakes", *Bull. Seismol. Soc. Am.*, **81**(5), 1754-1782.

Bolisetti, C., Whittaker, A.S., Mason, H.B., Almufti, I. and Willford, M. (2014) "Equivalent linear and nonlinear site response analysis for design and risk assessment of safety related nuclear structures", *Nuclear Eng. Des*., **275**(2014), 107-121.

Borcherdt, R.D. (1970), "Effects of local geology on ground notion near San Francisco Bay", *Bull. Seismol. Soc. Am*., **60**(1), 29-61.

Chamlagain, D. and Gautam, D. (2015a), "Seismic hazard in the Himalayan intermontane basins: An example from Kathmandu valley, Nepal", Eds., R. Shaw and H.K. Nibanupudi, Mountain Hazards and Disaster Risk Reduction, Chapter 5, Springer Japan.

Chamlagain, D. and Gautam, D. (2015b), "Assessment of urban seismic hazard due to 2015 Gorkha seismic sequence", Proceedings of the 14th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia, October 2015, Kathmandu.

Chamlagain, D., Lanzo, G., Pagliaroli, A. and Scasserra, G. (2013),"Numerical simulation of site effects in the upper Aterno valley array during the aftershock sequence of the 2009 L'Aquila earthquake", *Rivista*

Italiana di Geotechnica, **4**(2013), 8-23.

Chaulagain, H., Rodrigues, H., Jara, J., Spacone, E. and Varum, H. (2014), "Seismic response of current RC buildings in Nepal: A comparative analysis of different design/construction", Engineering Structures, 49(2013): 284-294.

Chitrakar, G.R. and Pandey, M.R. (1986), "Historical earthquakes of Nepal", *Bull. Geol. Soc. Nepal*, **4**, 7-8.

Enomoto, T., Navarro, M., Sánchez, F., Vidal, F., Seo, K., Luzón, F. and Romacho, M.D (1999), "Evaluación del comportamiento de los edificios en Almería mediante el análisis del ruido ambiental", *1a Asamblea Hispano-Lusa*, Aguadulce, Almería, Spain.

Erdik, M. (1987), "Site response analysis", Eds., MO Erdik and N Toksoz N, Strong Motion Seismology, Reidel Publishing Company.

Field, E.H. and Jacob, K.H. (1995), "A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent", *Bull. Seism. Soc. Am.*, **85**(4), 1127-1143.

Forte, G. and Santucci de Magistris, F. (2015), "Seismic permanent ground deformations: Analysis of soil liquefaction occurred after the 2012 Emilia Earthquake", *Rendiconti Online Societa Geologica Italiana*, **35**, 140-143.

Forte, G., Fabbrocino, S., Santucci de Magistris, F., Silvestri, F. and Fabbrocino, G. (2015), "Earthquake triggered landslides: The case study of a roadway network in Molise region (Italy)", Engineering Geology for Society and Territory - Volume 2: Landslide Processes, 765-768.

Gautam, D. and Chamlagain, D. (2015a), "Seismic hazard and liquefaction potential analysis of Tribhuvan International Airport, Nepal", *Proceedings of the7th Nepal Geological Congress*, Kathmandu, Nepal.

Gautam, D. and Chamlagain, D. (2016), "Preliminary assessment of seismic site effects in the fulvio-lacustrine sediments of Kathmandu valley, Nepal", *Nat. Haz.*, doi: 10.1007/s11069-016-2154-y.

Gautam, D., Bhetwal, K.K., Rodrigues, H., Neupane, P. and Sanada, Y. (2015), "Observed damage pattern during 2015 Gorkha (Nepal) earthquake", *Proceedings of the 14th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia*, Kathmandu.

Gautam, D., Chamlagain, D., Forte, G. and Poovordom, N. (2016), "Empirical correlation between standard penetration resistance (SPT-N) and shear wave velocity for soft soil deposit of Kathmandu valley, Nepal", Submitted paper in *Environmental Earth Sciences*, Springer.

Gautam, D., Rodrigues, H., Bhetwal, K.K., Neupane, P. and Sanada, Y. (2016), "Common structural and construction deficiencies of Nepalese buildings", *Innov. Infrastruct. Solut.*, doi: 10.1007/s41062-016-0001-3.

Gupta, S.P. (1988), *Eastern Nepal Earthquake 21 August 1988, Damage and Recommendations for Repairs and Reconstruction*, Asian Disaster Preparedness Center, Asian Institute of Technology, Bangkok, Thailand.

Hardin, B.O. and Dmevich, V.P. (1972), "Shear modulus and damping in soil: measurement and parameter effects", *J. Soil Mech. Found. Div.*, **98**(6), 603-624.

Hosseni, S.M.M.M. and Pajouh, M.A. (2010), "Comparative study on the equivalent linear and the fully nonlinear site response analysis approaches", *Arab J. Geosci.*, **5**(4), 587-597.

Iwan, W.D. (1967), "On a class of models for the yielding behavior of continuous and composite systems", *J. Appl. Mech.*, ASME, **34**, 612-617.

Iwata, T. and Irikura, K. (1988), "Source parameters of the 1983 Japan Sea earthquake sequence", *J. Phys. Earth*, **36**(4), 155-184.

Joyner, W.B. and Chen, A.T.F. (1975), "Calculation of nonlinear ground response in earthquakes", *Bull. Seismol. Soc. Am.*, **65**(5), 1315-1336.

Kaklamanos, J., Bradley, B.A., Thompson, E.M. and Baise, L.G. (2013), "Critical parameters affecting bias and variability in site-response analyses using KiK-net Downhole Array Data", *Bull. Seismol. Soc. Am.*, **103**(3), 1733-1749.

Katel, T.P., Upreti, B.N. and Pokharel, G.S. (1996), "Engineering properties of fine grained soils of Kathmandu Valley, Nepal", *J. Nepal Geol. Soc.*, **13**, 121-138.

Kim, B., Hashash, Y.M.A., Kottke, A.R., Assimaki, D., Li, W., Rathje, E.M., Campbell, K.W., Silva, W.J. and Stewart, J.P. (2013), "A predictive model for the relative differences between nonlinear and equivalent-linear site response analyses", *Proceedings of the 22nd International Conference in Structural Mechanics in Reactor Technology*, San Francisco, CA.

Lam, I., Tsai, C.F. and Martin, G.R. (1978), "Determination of site dependent spectra using nonlinear analysis", *Proceedings of 2nd International Conference on Microzonation*, San Francisco, CA.

Lanzo, G., Silvestri, F., Costanzo, A., d'Onofrio, A., Martelli, L., Pagliaroli, A., Sica, S. and Simonelli, A. (2011), "Site response studies and seismic microzoning in the Middle Aterno valley (L'Aquila, Central Italy)", *Bull. Earthq. Eng.*, **9**(5), 1417-1442.

Lermo, J. and Chavez-Garcia, F.J. (1993), "Site effects evaluation using spectral ratios with only one station", *Bull. Seismol. Soc. Am.*, **83**(5), 1574-1594.

Maskey, P.N. and Dutta, T.K. (2004), "Risk consistent response spectrum and hazard curve for a typical location of Kathmandu valley", *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver BC, Canada.

Moribayashi, S. and Maruo, Y. (1980), "Basement topography of the Kathmandu Valley, Nepal-An application of gravitational method to the survey of a tectonic basin in the Himalayas", *J. Japan Soc. Eng. Geol.*, **21**(2), 30-37.

Mroz, Z. (1967), "On the description of anisotropic work hardening", *J. Mech. Phys. Solid.*, **15**(3), 163-175.

Nakamura, Y. (1988), "On the urgent earthquake detection and alarm system (UrEDAS)", *Proceedings of the World Conference in Earthquake Engineering*.

NEHRP (1994) "Recommended Provisions for New Buildings", Building Seismic Safety Council, Washington, DC.

Pandey, M.R., Tandukar, R.P., Avouac, J.P., Lave, J. and Massot, J.P. (1995), "Interseismic strain accumulation in the Himalayan crustal ramp (Nepal)", *Geophys. Res. Lett.*, **22**(7), 751-754.

Pandey, M.R., Tandukar, R.P., Avouac, J.P., Vergne, J. and Heiritier, T. (1999), "Seismotectonics of the Nepal Himalaya from a local seismic network", *J. Asian Earth Sci.*, **17**(5), 703-712.

Paudyal, Y.R., Bhandary, N.P. and Yatabe, R. (2012), "Seismic microzonation of densely populated area of Kathmandu valley of Nepal using microtremor observations", *J. Earthq. Eng.*, **16**(8), 1208-1229.

Paudyal, Y.R., Yatabe, R., Bhandary, N.P. and Dahal, R.K. (2012), "Study of local amplification effect of soil layers on ground motion in the Kathmandu valley using microtremor analysis", *Earthq. Eng. Eng. Vib.*, **11**(12), 257-268.

Psarropoulos, P.N., Gazetas, G. and Tazoh, T. (1999), "Seismic response analysis of alluvial valley at bridge site", *Proceedings of the 2nd International Conference in Earthquake Geotechnical Engineering*, Lisbon.

Psarropoulos, P.N., Tazoh, T., Gazetas, G. and Apostolou, M. (2007), "Linear and nonlinear valley amplification effects on seismic ground motion", *Soil Found.*, **47**(5), 857-871.

Safak, E. (2001), "Local site effects and dynamic soil behavior", *Soil Dyn. Earthq. Eng.*, **21**(2001), 453-458.

Sakai, H. (2001), "Stratigraphic division sedimentary facies of the Kathmandu basin group, Central Nepal", *J. Nepal Geol. Soc.*, **25**, 19-32.

Santucci de Magistris, F., d'Onofrio, A., Penna, A., Puglia, R. and Silvestri, F. (2014), "Lessons learned from two case histories of seismic microzonation in Italy", *Nat. Haz.*, **74**(3), 2005-2035.

Santucci de Magistris, F., Lanzano, G., Forte, G. and Fabbrocino, G. (2014), "A peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy)", *Nat. Haz.*, **74**(2), 1069-1094.

Seeber, L. and Armbruster, J. (1981), "Great detachment earthquakes along the Himalayan arc and the long term forecasts", Eds., E.W. Simpson and P.G. Richards, Earthquake Prediction: An International Review, Maurice Ewing Series 4. American Geophysical Union Washington, DC.

Seed, H.B. and Idriss, I.M. (1970), *Soil Moduli and Damping Factors for Dynamic Response Analysis*, Report No. EERC7 0-10, University of California, Berkeley.

Semblat, J.F., Kham, M., Bard, P.Y. and Gueguen, P. (2004), "Could 'site-city interaction' modify site effects in urban areas?", *Proceedings of 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada.

Stocklin, J. and Bhattarai, K.D. (1977), *Geology of Kathmandu Area and Central Mahabharat Range, Nepal* Himalaya, HMG/UNDP Mineral Exploration project, Kathmandu.

USGS (United States Geological Survey) (2011), http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0005wg6/

Vucetic, M. and Dobry, R.J. (1991), "Effect of soil plasticity on cyclic response", *J. Geotech. Eng.*, ASCE, **117**(1), 89-117.

Yamazaki, F. and Ansary, M.A. (1997), "Horizontal-to-vertical spectrum ratio of earthquake ground motion for site characterization", *Earthq. Eng. Struct. Dyn.*, **26**(7), 671-689.

Yoshida, M. and Igarashi, Y. (1984), "Neogene to Quaternary lacustrine sediments in the Kathmandu valley, Nepal", *J. Nepal Geol. Soc.*, **4**, 73-100.

KT