Ground Response Based Preliminary Microzonation of Kathmandu Valley

Dipendra Gautam[1*], Hemchandra Chaulagain[2], Hugo Rodrigues[3] and Hem Raj Shahi[4]
[1]*Structural and Earthquake Engineering Research Institute, Kathmandu, Nepal*
[2]*Department of Civil Engineering, Oxford College of Engineering and Management, Pokhara University, Nepal*
[3]*RISCO, School of Technology and Management, Polytechnic Institute of Leiria, Leiria, Portugal*
[4]*RIDARC, Nepal*
[*]*Email: strdyn@yahoo.com*

ABSTRACT: This paper analyzes spatially selected 286 deep borehole logs reaching up to the bedrock and the results are presented in terms of amplification factor, ground acceleration and predominant period. The peak ground acceleration (PGA) is estimated to be 0.10 and 0.50 g indicating strong influence of nonlinearity in particular areas of Kathmandu valley wherein de-amplification is observed. The peak spectral acceleration is found to be varying from 0.30 to 1.75 g for the study area and soil predominant period is estimated in the range of 0.7 to 5 sec. Preliminary microzonation maps for PGA and soil predominant period are prepared and presented in this paper. Comparisons and interpretations on the basis of 1934 and 2015 earthquakes are presented in terms of damage scenario.

KEYWORDS: Hazard mapping, Nonlinear ground response analysis, Amplification factor, Peak ground acceleration, Soil predominant period; Kathmandu valley.

1. INTRODUCTION

Geological, geophysical and geotechnical characteristics of local soil have paramount effects in seismic ground motions. The 1906 San Francisco and 1923 Kanto earthquakes have rectified the strong correlation between sub-surface geology and earthquake damage. Deep valleys with abundance of soft soils have been highlighted further during earthquakes due to variation in soil behavior within a small distance. Correlation between earthquake ground motion and the amplification characteristics of local geology has been highlighted in studies all over the world (Aki and Larner 1970; Aki 1993; Psarropoulos et al. 1999; Semblat et al. 2004; Psarropoulos et al. 2007; Chamlagain and Gautam 2015; Gautam and Chamlagain 2016). Recent advances in geotechnical earthquake engineering have led to delineate a proper soil response in terms of amplification, ground motion and soil predominant periods (Schnabel et al. 1972; Bardet et al. 2000; Hashash et al. 2008). While incorporating site-specific risk assessment, earthquake hazard parameters, ground shaking intensity, liquefaction, lateral ground spreading and settlement susceptibility, surface faulting and tectonic deformation, earthquake induced slope stability problems and earthquake induced flooding among others are to be included. After 1964 Nigata and San Francisco, 1980 Irpina, 1985 Mexico City, 1995 Kobe, 2015 Gorkha and several other earthquakes indicated that the local amplification of earthquake ground motion is one of the most significant factors in non-uniform structural damage basically in soft soil deposits.

The 1934 Bihar-Nepal earthquake (M_W 8.1) in Kathmandu valley caused 19 % of buildings collapsed and 38 % of buildings damaged though the epicenter was located at some 250 km from Kathmandu valley and causing 4296 casualties (Rana 1935; Pandey and Molnar 1988). Moreover, Rana (1935) and Pandey and Molnar (1988), highlighted the concentration of damage was particularly intense in the areas comprising loose, unconsolidated soil deposits like Bhaktapur. Japan International Cooperation Agency (JICA) in 2002 estimated for the scenario of repetition of 1934 earthquake as many as 59000 houses would be destroyed, 18000 deaths and 59000 seriously injured in Kathmandu valley. Many studies have shown usually high amplification and ground shaking and also shown possibility of vibration resonance during earthquakes for Kathmandu valley (Maskey and Dutta 2004; Paudyal et al. 2012; Chamlagain and Gautam 2015; Gautam and Chamlagain 2015; Parajuli and Kiyono 2015; Gautam and Chamlagain 2016; Gautam et al. 2016a) such amplification was identified as one of the major cause of damage during Mexico City earthquake as well (Celebi et al. 1987). Similar geological condition, construction practices and workmanship and location in one of the most active convergence plate boundary may even surpass the damage level in Kathmandu valley as that of Mexico City.

Even in small strain condition, soil possesses nonlinear behavior; however previous studies are confined in either linear or equivalent linear formulation only in case of Kathmandu valley (e.g. Chamlagain and Gautam 2015; Gautam and Chamlagain 2015; Gautam and Chamlagain 2016). With due account of soil nonlinearity this study incorporates the soft soil deposit of Kathmandu valley in terms of nonlinear seismic site response analyses and the parameters are plotted to develop a preliminary scenario based microzonation maps for soft soil deposit parts of Kathmandu valley.

2. GEOLOGY OF STUDY AREA

Kathmandu valley consists of thick fluvio-lacustrine deposit of Pliocene to Quaternary age in the Lesser Himalaya Zone of Nepal and the sediment thickness is reported to be upto 500 m (Yoshida and Igarashi 1984). Kathmandu valley soil is primarily characterized by occurrence of fluvio-lacustrine unconsolidated sediments in the central portion and outcropping bedrock in peripheral regions. The central portion of valley has gotten largest thickness and diminishes in peripheral regions. Sediment deposit in Kathmandu valley is non-uniform (Figure 1). Tarebhir Fault and Chandragiri Fault situated in the southern part of Kathmandu valley are considered as the active faults and these two faults are found to be intersecting the colluvial slopes and terraces of the late Pleistocene age (Sakai 2001).

Central valley is composed of Bagmati Formation, Kalimati Formation and Patan Formation, meanwhile Bagmati Formation was active before the lake formation in Kathmandu valley and considered as a responsible factor for sediment deposition in majority areas of Kathmandu valley. The Kalimati Formation is dominantly occurring in present day central valley with grey carbonaceous beds of the lacustrine facies and characterized by occurrence of black cotton soils. Most of the areas in major administrative center of Nepal are comprised of Patan Formation which consists of fine to medium sand and silt inter-bedded with clay and fine gravels at some sites. Gokarna Formation and Thimi Formation are dominant over northern and northeastern part of Kathmandu valley which consists of fluvio-deltaic or fluvio-lacustrine origin and primarily sandy facies [Yoshida and Igarashi 1984; Sakai 2001). Kathmandu valley basement rock is composed of Phulchoki Group and Bhimphedi Group of the Kathmandu Complex (Stocklin and Bhattarai 1977).

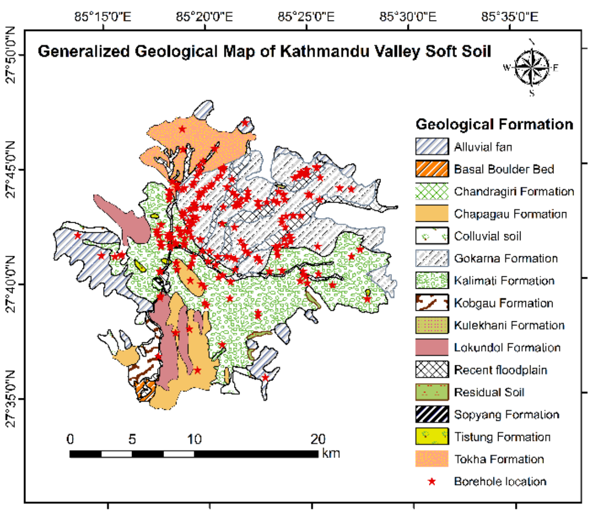


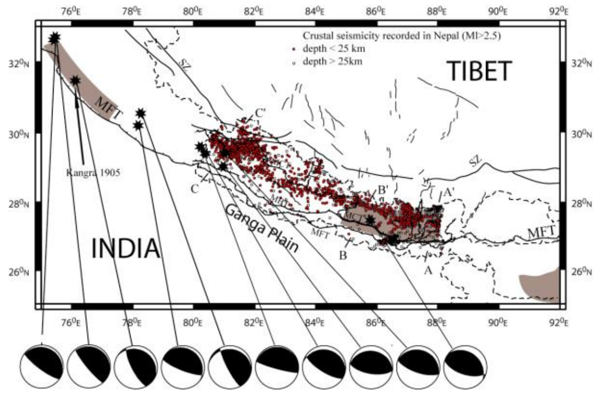
Figure 1 Generalized geological map showing borehole locations

3. SEISMICITY

Over past few centuries the Himalayan arc is experiencing major earthquakes in regular intervals indicating entire Hind-Kush-Himalaya as seismically one of the most active region of the world (e.g. 1897 Shillong earthquake, $M_w = 8.1$; 1905 Kangra earthquake, $M_w = 7.8$; 1934 Bihar-Nepal earthquake, $M_w = 8.1$; 1950 Assam earthquake $M_w = 8.7$; 1988 Udaypur earthquake $M_w = 6.5$; 1991 Uttarkashi earthquake, $M_w = 6.9$; 2005 Kashmir earthquake $M_w = 6.2$, 2011 Sikkim-Nepal boarder earthquake, $M_w = 6.9$ and 2015 Gorkha earthquake M_W =7.8. The rupture length of Himalayan arc is identified to be several hundreds of kilometers after aforementioned events (Seeber and Armbruster 1981; Bilham et al. 1995; USGS 2011). While accounting the earthquakes after 1800, the slip deficit is depicted for around 60% of the arc as 4 m, which may cause several major earthquakes in the entire Hind-Kush-Himalayan region with possibility of 10 m slip depending on the reliability of the historic record prior to these events (Bilham et al. 1997). Evidently, the central seismic gap seems to be dormant since 1505 and potential slip at this region is estimated up to 9 m with the assumption that the fault is fully locked and would be responsible for earthquakes of M_W>8 (Bilham and Ambraseys 2004).

The intense micro-seismicity distribution clustered within Nepal Himalaya disseminates three distinct clusters (Pandey et al. 1999). The cluster is located between 86.5^{0}E and 88.5^{0}E in eastern Nepal, 82.5^{0}E and 86.5^{0}E in central Nepal and 80.5^0 E and 82.5^{0}E in western Nepal. The great Himalayan earthquakes are considered to be following the basal decollement beneath the Siwalik and Lesser Himalaya and the focal depth varying between10-20 km (Figure 2). The trend of earthquakes in Nepal Himalaya is of predominantly occurring moderate-sized earthquakes below the Lesser Himalayan

and just south of the Higher Himalayan front. The mid-crustal ramp model has illustrated the mechanism of earthquake generation in the Himalaya; depicting that during inter-seismic periods due to locking of southern ramp-flat segment of Main Himalayan Thrust (MHT). The strain is being accumulated over this and upon exceedance in threshold; the accumulated stress would lead in major earthquakes along the MHT (Pandey et al. 1999). Past events of 1255, 1408, 1681, 1803, 1810, 1833, 1866, 1934, and 1988 have severely devastated Kathmandu valley in terms of casualties, infrastructural damage and properties loss (Chitrakar and Pandey 1986; Bilham et al. 1995; Gupta 1988; Pandey et al. 1995). Evidently, Kathmandu valley is regarded as one of the high earthquake risk area and the severity is further amplified by its location, population concentration, fragile and unconsolidated soft soil deposit and haphazard construction practices.



Stars represent medium size earthquake

Figure 2 Seismicity in the Himalayas of Nepal after (Jouanne et al. 2004); the intense micro-seismicity (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

4. GEOTECHNICAL CHARACTERIZATION OF STUDY AREA

Kathmandu valley is an intermountain basin composed of fluvio-lacustrine sediment deposits. Moribayashi and Maruo (1980) estimated the thickness of Kathmandu valley soft soil upto 650 m by gravity measurements. However, Katel et al. (1996) estimated a muddy and sandy sequence of more than 300 m thickness from drilling data at various sites. Thick unconsolidated black cotton soil is widely distributed in soft soil sites of Kathmandu valley, primarily the domination of such soil could be found in the central part. Analysis of 286 deep boreholes reaching up to the bedrock has led us to formulate that, there is alternating sequence of silt and sand within the soft soil deposit of Kathmandu valley; moreover, clay is occurring in some sites however most of the sites comprise a mixture of silty clay, sandy clay, clayey silt and silty sand (Figure 3).

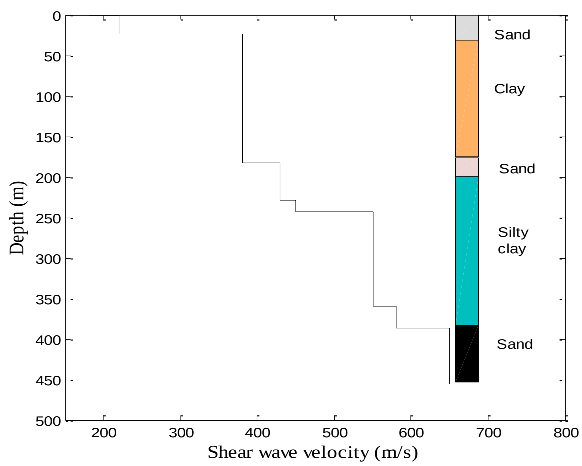


Figure 3 Representative vertical shear wave velocity variations in a borehole

Within small spatial and temporal variation, variation in soil type and drastic variation in geotechnical characteristics is observed within the Kathmandu valley. The uppermost layer is usually comprised of vegetable top soil or filling materials followed by either silt or sand or the mixture of both thereafter. A representative borehole log and its geotechnical characterization are shown in Figure 3, and suggest the inter-bedding amongst sand, silt and clay or their mixture. Usually, domination of sand and silt could be observed in boreholes drilled across the study area.

5. METHODOLOGY

5.1 Nonlinear One Dimensional Seismic Site Response Analysis

Soils possess nonlinear behaviour even in small strains; so in order to perform an exact nonlinear modelling of seismic site effects with true nonlinear constitutive models are incorporated with a numerical code Nonlinear Earthquake Site Response Analysis (NERA) developed by University of Southern California (Bardet and Tobita 2001). Previous studies within Kathmandu valley are confined to either linear or equivalent-linear only (e.g. Maskey and Dutta 2004; Chamlagain and Gautam 2015; Gautam and Chamlagain 2016), however Chamlagain and Gautam (2015) indicated that there is strong possibility of soil nonlinearity within Kathmandu valley. In order to incorporate the exact soil behaviour, nonlinear site response is performed for spatially distributed 286 deep borehole logs reaching up to the bedrock. One dimensional seismic site effects is incorporated in terms of amplification factor, peak spectral acceleration, peak ground acceleration and soil predominant period.

Figure 4 depicts the fundamental concept of one dimensional seismic site response analysis. One dimensional ground response analysis base on assumption of infinite horizontal layering of soil is performed subjecting a horizontal motion at the bedrock level. Subsequent modifications of parameters in each node are accounted through iterative approach created as node in each layer. Moreover, in the case of one dimensional analysis, the shear wave velocity propagation is considered to be propagating vertically and thus the governing equation could be written as:

$$\rho\frac{\partial^2 d}{\partial t^2}+\eta\frac{\partial d}{\partial t}=\frac{\partial \tau}{\partial z} \qquad (1)$$

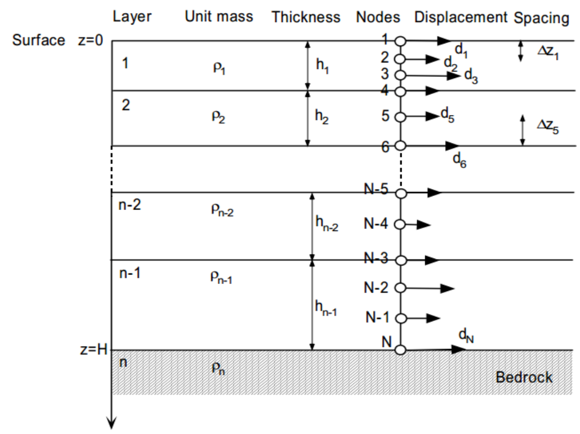


Figure 4 One dimensional layered soil system and spatial discretization (after Bardet and Tobita 2001)

Wherein ρ *is* the unit weight of soil; d is the horizontal displacement; z is the depth; t is the time; τ is the shear stress and η is the mass proportional damping coefficient. The boundary condition is accounted as: for the free surface z=0 and at the bedrock level z=H as specified in Figure 4. The ground motion is imposed on the bedrock layer and subsequent modifications in parameters are calculated through at least 15 iterations (see details in Bardet and Tobita 2001).

For preliminary microzonation mapping in terms of peak ground acceleration and soil predominant period, shear profiles and material curves are adopted. As there is no any available database for the shear wave velocity profiling for deep boreholes, Mississippi embayment shear profile (for details see Cramer 2006) is adopted for analysis. Till date dynamic soil characteristics aren't studied for Kathmandu valley, so for this analysis purpose, soil moduli as suggested by Seed and Idriss (1970) are used (Figure 5).

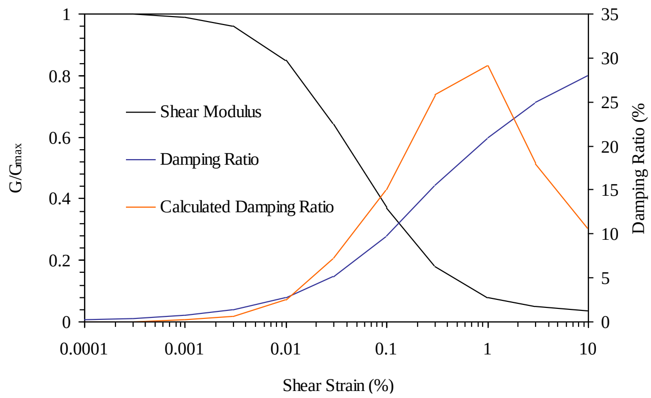


Figure 5 Modulus for sand after Seed and Idriss (1970)

5.2 Input Motion

Uttarkashi earthquake (M_w = 6.9) of 20 October 1991 is used as the input motion in this study. The time history of this earthquake was recorded at an epicentral distance of 34 km at Uttarkashi station on bedrock. The type and tectonic setting of Uttarkashi earthquake are coinciding with the earthquake scenario in Nepal Himalaya, thus for better modeling of Kathmandu valley, the motion is chosen. The epicentral distance seems to be matching with the existing possible sources of earthquakes (MBT and MFT) around Kathmandu valley. The double cycle acceleration time history recorded in Uttarkashi station shows the peak ground acceleration 0.32 g at 5.86 sec (Figure 6) and the corresponding peak spectral acceleration is 1.3 g at 0.29 sec (Figure 7).

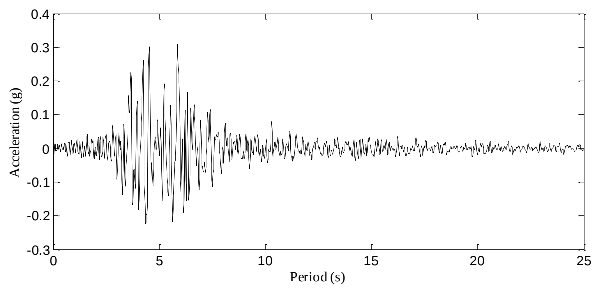


Figure 6 Acceleration time history of Uttarkashi earthquake

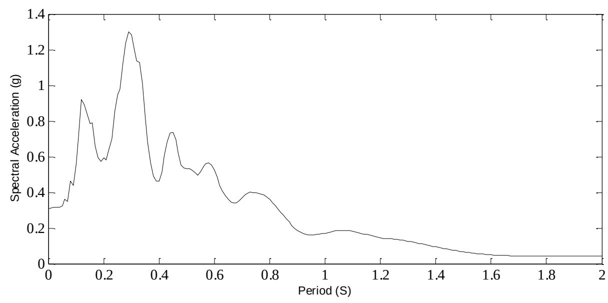


Figure 7 Response spectra for Uttarkashi earthquake

6. RESULTS AND DISCUSSION

This study simulates altogether 286 borehole logs using one dimensional NERA code. In order to understand the preliminary nonlinear soil behaviour in Kathmandu valley soft soils, various surface parameters are incorporated in this study and the results are discussed in the following sections.

6.1 Peak Ground Acceleration

The Peak Ground Acceleration (PGA) in the study area varies between 0.10 to 0.50 g (Figure 8). The higher PGA along with the higher amplification might be severe in terms of structural damage in Kathmandu valley during future events. As depicted by Figure 8, majority of soft soil locations in case of strong scenario earthquake of magnitude 6.9 are predicted to be de-amplified. The variation in spectral acceleration is estimated between 0.30 and 1.75 g. Representative acceleration response spectra are plotted in Figure 9. In particular, higher PGA is found to be concentrated in Kalimati Formation (see Figure 1) along with greater spectral amplification. However, Gokarna Formation, Lukundol Formation, and Alluvial Fan Formation are estimated to be highly de-amplified in case of deep borehole analysis for a strong earthquake. The wider variation of response spectra in the range of 0.1 to 0.8 sec represent the possibility of more localized damage during earthquakes and is well justified during 2015 Gorkha earthquake. During Gorkha earthquake, some of the designed structures were completely collapsed in particular areas of Kathmandu valley however some substandard RC and masonry structures survived appreciably. As the peak spectral acceleration in the entire soft soil deposit of Kathmandu valley has higher values, possible damage in future may be well accompanied by such higher ground shaking incorporated by very high spectral amplification.

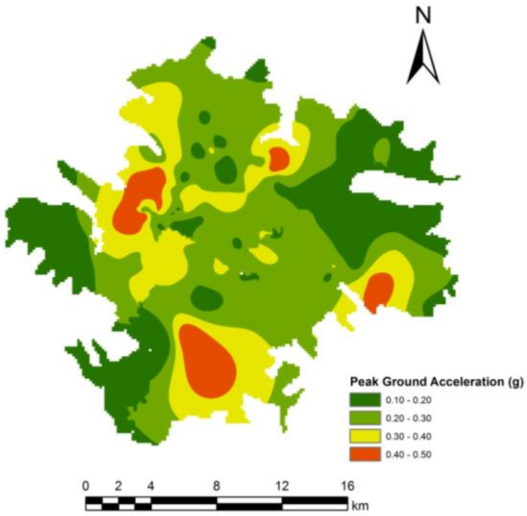


Figure 8 Distribution of PGA in Kathmandu valley

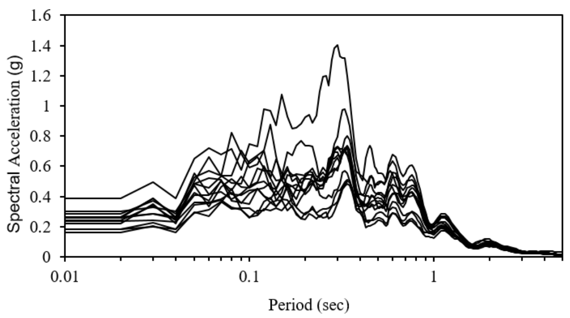


Figure 9 Representative acceleration response spectra at 5% damping in Kathmandu valley

6.2 Soil Predominant period

The soil predominant period in the study area is estimated to be 0.7 to 5.0 sec (Figure 10). During earthquakes, the soil-structure resonance phenomenon might be instrumental. Soil predominant period is particularly concerned along with the structural time period. Thus predominant period of this range would be pivotal in terms of seismic demand of structures in Kathmandu valley. Present day construction trend shows the dominance of middle to high rise structures, surely those structures have the time period in between 0.7 to 5.0 sec, this may be possible cause of devastation of many structures during future earthquakes. Notably, during Gorkha earthquake, high rise apartments and towers suffered countable damage in particular locations in comparison to mud-mortar brick masonry structures, the estimated variation of soil predominant period appreciably explains such cause particularly in vibration resonance aspect. Higher predominant period is found to be concentrated in the south-west portion of valley in Lukundol and Chapagain Formation including some parts constituting Alluvial Fan Formation, whereas majority areas have the predominant period to be 0.70 to 2.5 sec.

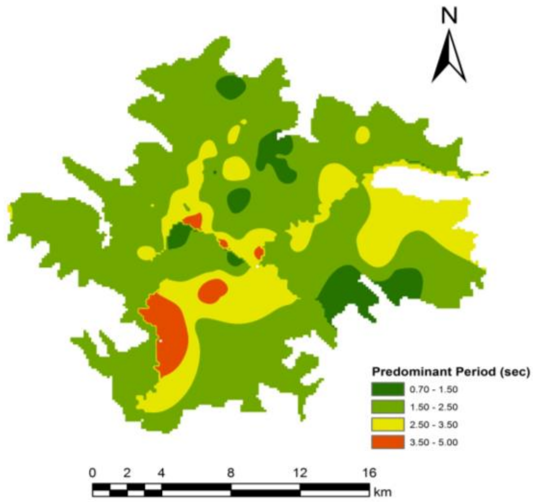


Figure 10 Predominant period in Kathmandu valley

6.3 Critical Review of Findings with Reference to 2015 Gorkha Earthquake

On 25 April 2015, a strong earthquake of M_W 7.8 struck central Nepal and the vicinity. The Gorkha seismic sequence is still active while writing this paper and till now more than 450 aftershocks of M_L>4 are recorded. The significant aftershocks of 26 April (M_W 6.7) and 12 May (M_W 7.3) are also responsible for widespread damage of structures in central, western and eastern Nepal. The majority of structural damage is concentrated in substandard and low strength masonry structures in earthquake affected areas. The areas in the valley edge are found to be having some serious damages in reinforced concrete structures. The results of this analysis are found to be consistent in terms of structural damage in the northwestern part of Kathmandu valley as suggested by very high amplification and considerably large values of PGA. As the 2015 Gorkha earthquake was not comparable to Uttarkashi earthquake in terms of PGA, thus the exhaustive representation of results was not tested, however the severely damaged areas are also characterized by higher values of spectral amplification and considerably large PGA. On the contrary, the de-amplification of surface motion is well justified during Gorkha earthquake. The central valley is predicted to be de-amplified for this particular type of earthquake, which also acquaints with the observations after Gorkha earthquake. Even though the soil characteristics seems to be very loose alluvial type, however damage was concentrated in typical locations only (for details see: Gautam et al. 2016b; Gautam and Chaulagain 2016) rather than the central valley. Due to unavailability of the measured shear profiles for deep boreholes, lack of nonlinear material backbone curves, density and plasticity of each layer, the exact modeling is still needed for Kathmandu valley for delineating the exact behavior during earthquakes. During two of the strong earthquakes of 1833 and 1934, localized damage was also particularly reported (Rana 1935) and recent evidences of 2015 Gorkha earthquake verify the localized damage scenario and also strong influence of soil nonlinearity is observed. Interestingly, the edges of valley are historically suffered more than other areas as per the paradigms of 1833, 1934 and 2015, this study also justifies with the occurrence of higher PGA in peripheral locations. In the other hand, the lowest PGA is obtained to be 0.10 g; this is well above the PGA threshold criteria of 0.09 g estimated by Santucci de Magistris et al. (2014) so possibility of liquefaction within Kathmandu valley cannot be denied in case of future earthquakes as the central valley observed liquefaction during 1934 and peripheral valley locations observed some cases of liquefaction during 2015 Gorkha earthquake. Local soil response has been transparently reflected during Gorkha earthquake, however very few previous studies modeled the nonlinear soil behavior in and exhaustively justified the de-amplification. In this regard, further field measurements and dynamic soil modeling are highlighted for understanding the exact and site specific soil behavior. In addition, the existing building code in Nepal now seems strictly unrepresentative due to strong influence of local soil behavior, thus site categorization and development of site-specific design considerations are immediately needed.

7. CONCLUSIONS

The nonlinear one dimensional site seismic site response analysis of soft soil deposits of Kathmandu valley is performed using the NERA code for 286 deep borehole logs reaching upto bedrock and results are obtained in terms of peak ground acceleration, spectral acceleration, and predominant period. The peak ground acceleration within the study area is estimated to be varying between 0.10 to 0.50 g suggesting that majority of valley locations undergo de-amplification during strong earthquakes when considered the overall alluvial deposit for analysis. Apart from this, the peak spectral acceleration is estimated in the range of 0.30 to 1.75 g across Kathmandu valley alluvial Formations. This value suggests a very high occurrence of absolute acceleration in particular areas and might lead in severe damage in future. Such higher values are found to be concentrated in the loose and black cotton soil deposits of Kathmandu valley in some areas. In the other hand, the predominant period is estimated in the range of 0.7 to 5 sec. For structural engineering purpose and design and consideration of special types of structures, seismic demand is important and typical structures susceptible of vibration resonance should be thoroughly considered with this vibration resonance. This justifies the immediate need of site categorization and development of site-specific design consideration criteria for Kathmandu valley. For basic understanding of local soil behavior preliminary microzonation maps are prepared and the map highlights the dominant paradigm of soil nonlinearity with de-amplification mechanism in many areas within Kathmandu valley. In addition, the seismic demand analysis in case of high rise structures having time period 0.7 sec or above should be carefully determined for similar earthquake scenario.

8. ACKNOWLEDGEMENT

Authors are grateful to Mr. Suraj Ojha, Mr. Murali Deo, Dr. Deepak Chamlagain and Mr. Niroj Maharjan for providing several databases. Constructive discussions from the reviewers are also acknowledged.

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