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One Dimensional Ground Response analysis in Patan: Implications to Damage Pattern due to the 2015 Mw 7.8 Gorkha Earthquake

Govinda Prasad Niroula[*, 1], Deepak Chamlagain[2] and Indra Prasad Acharya[3]
[1]Department of Civil Engineering,Kathford International College of Engineering and Management, (affiliated to Tribhuvan University), Balkumari, Lalitpur
[2]Department of Geology, Tri-Chandra Multiple Campus, Tribhuvan University, Kathmandu
[3]Department of Civil Engineering, Pulchok Campus, Tribhuvan University, Lalitpur

*Corresponding author: *govind.niroula@gmail.com*

ABSTRACT: The 2015 Mw 7.8 Gorkha earthquake caused extensive damages in Kathmandu Valley located about 78 km SE from the epicenter. The damage patterns in the city clearly indicated the subsurface geology of the city had strongly modified the ground motion causing typical damages to tall structures. In this contribution, following one-dimensional approach, a ground response analysis is performed in Patan utilizing the deep borehole, shear wave profile and dynamic soil properties adopting both equivalent linear and non-linear approaches. The results of both equivalent linear and non-linear analyses were compared with the measured ground motions at soil site. It is found that the non-linear analysis better simulates the deamplification of the peak ground acceleration and strong shaking at longer period than the equivalent linear analysis. The obtained results confirm that the deamplification of PGA was due to the strong non-linear behavior of the fluvio-lacustrine deposits.

KEYWORDS: Gorkha Earthquake, Seismic site effects, Ground Motion

1. INTRODUCTION

After the 1906 San Francisco, U.S.A. and 1923 Kanto earthquakes, Japan, it has been widely perceived that sub-surface geology and earthquake damage have strong correlation. Local sub-surface geology, geomorphology, basin geometry and the geotechnical characteristics of the soil strata have a strong amplification of seismic ground motion, a main cause for massive damage. Such effects are usually termed as seismic effects. Numerous studies on seismic site effects (Aki and Larner, 1970; Aki, 1993; Semblat et al., 2004; Psarropoulos et al. 1998; Psarropoulos, et al., 2007) have now well established the facts that local geology, topography, valley morphology and epicentral distance to the site have great influence on modification of strong ground motion.

The Mw 7.8 Gorkha earthquake of 25th April, 2015 hit central Nepal at 11:56 AM. The epicenter of the thrust type inter-plate earthquake was at Barpak Village of the Gorkha district and focal depth of the earthquake was at 15 km. In the event, significant damage was mostly observed in central Nepal. During this earthquake, Kathmandu Valley suffered a lot reflecting the significant modification of seismic waves that caused massive damages.

In this contribution, it is aimed to carry out 1D seismic site effects assessment in Patan area, Kathmandu Valley based on the measured shear wave velocity, geotechnical properties of the soil strata adopting both equivalent linear and non-linear approaches. The strong ground motion of the main shock of the 2015 7.8 Mw Gorkha earthquake is used as input motion. A comparative study of measured and computed response spectra is carried out to understand damage pattern.

1.1 Geo-tectonics setting

Geologically, Kathmandu Valley, an intermontane basin is located in the metamorphic nappe consisting of low to medium grade metamorphic rocks, which is overlain by the fossiliferous rocks of Tehyan origin. The geology of the valley is basically characterized by the basement rocks of the Kathmandu Complex and the soft sediments of fluvio-lacustrine origin (Stocklin and Bhattarai, 1981).

The basin-filled fluvio-lacustrine sediments of the Kathmandu Valley belong to Pliocene to Pliestocene age (Yoshida and Igarashi, 1984). Based on the gravity survey in the valley, Moribayashi and Maruo (1980) estimated maximum thickness of about 650 m. The drill hole at the Bhrikutimandap shows a bedrock depth at 550 m. Based on the drill cores, the basin fill sediments broadly divided into three formations, namely Bagmati Formation, Kalimati Formation and Patan Formation from bottom to top (Sakai, 2001). The Bagmati Formation is characterized by sand

and gravel beds at the basal part of the Kathmandu Valley and is considered as the northern continuation of the Tarebhir Formation in the southern part (Figure 1). The overlying Kalimati Formation is characterized dominantly by laminated fossiliferous black clay. The fluvial beds of the Patan Formation lies on the Kalimati Formation and is mostly characterized by the medium grained sand beds extensively distributed in the northern part (Sakai, 2001).

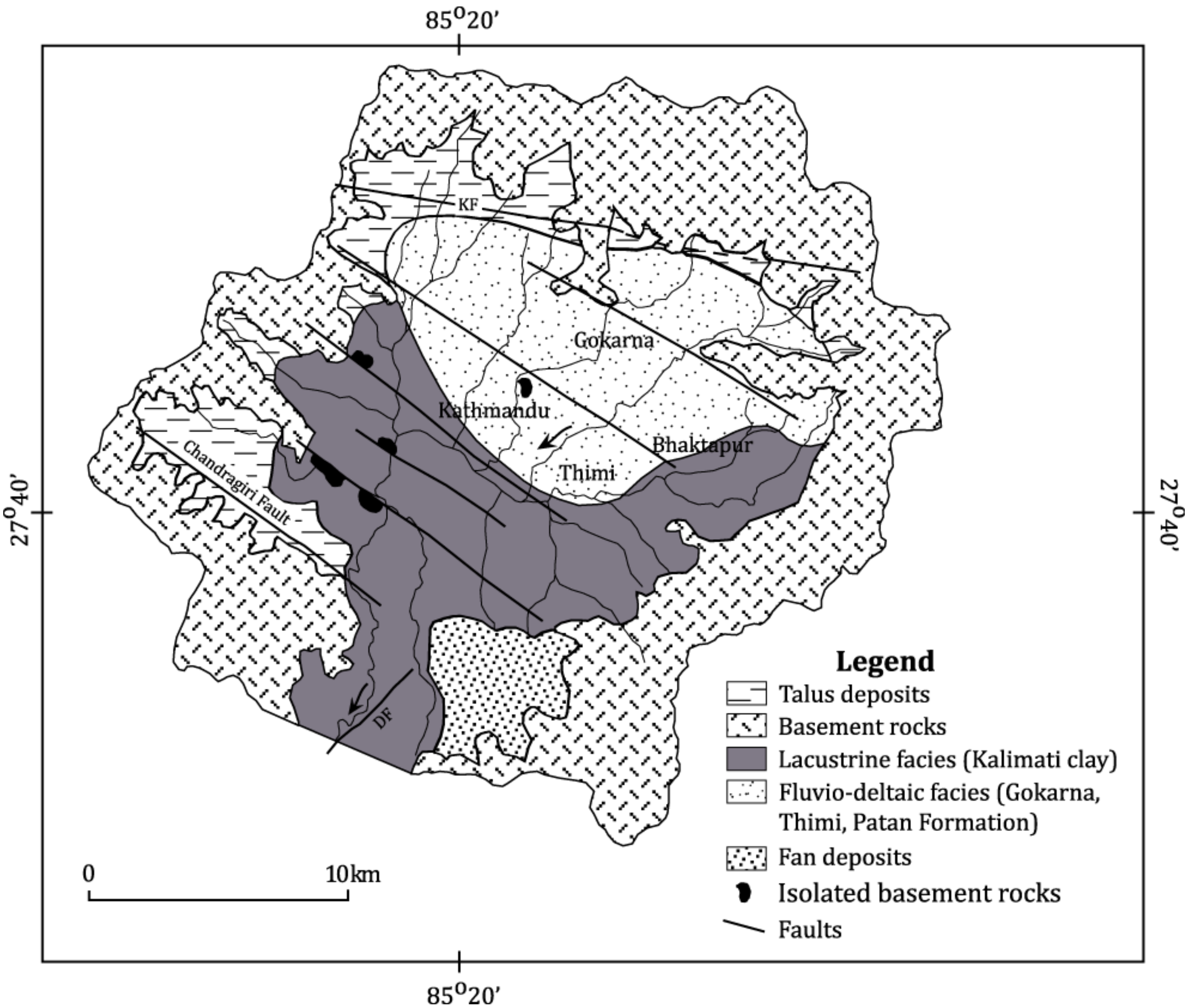

Figure 1. Geological map of Kathmandu Valley (Reproduced with permission from Sakai, 2001)

1.2 The 2015 Gorkha Earthquake

The 2015 Gorkha earthquake disaster was the medium scale earthquake disaster after the 1934 Bihar-Nepal earthquake. The earthquake occurred close to Kathmandu Valley and the epicenter was located 80 km to the northwest of Kathmandu within a long-identified zone of clustered seismicity that runs beneath the front of the high Himalaya. The earthquake was initiated at the hinge point of the ramp along the previously locked MHT (Avouac et al 2015). The rupture was propagated towards east for about 140 km. The Gorkha seismic sequence was arrested after the major aftershock of May 12, 2015 with magnitude 7.3 that occurred in Sindhuplachok, east of Kathmandu. The aftershocks are continuous till date, more than 500 aftershocks of magnitude greater than Ml 4 were recorded. More than 24,000 landslide were mapped in the rupture zone and interestingly, these landslides were not correlated with the peak ground acceleration (Robback et al. 2017). The landslides were mainly of due to perturbation of the threshold slope of the mountain slope. Scattered liquefaction in the Kathmandu Valley and extensive ground fissure in the mountain slopes were found. Altogether 8,970 people were killed and around 22,000 were seriously injured. Beside human loss, about one-million houses were damaged at different scale in the affected region (MoHA 2016). The intensity of the damage was increased to the east of epicenter probably due to the effect of rupture directivity.

1.2.1 Strong Ground Motion

Before the Gorkha earthquake, the network established by Hokkaido University, Japan in collaboration with Tribhuvan University, Nepal was the functional network, which has four stations one in rock site (KTP) in Kirtipur, southern part of the Kathmandu Valley and remaining three are located in soil sites at Central Department of Geology, Tribhuvan University (TVU), Pulchok Campus, Patan (PTN) and University Grant Commission, Thimi Bhaktapur (THM) in the Kathmandu Valley (Takai, 2016). These all stations have measured the ground motion of the Gorkha seismic sequence.

The strong ground motions of the Gorkha seismic sequence are characterizing by typical features (Figure 2). At KTP, the peak horizontal acceleration along the EW direction was 0.15g, whereas for the EW component was 0.24g and vertical acceleration was 0.12g. In contrast, at the sedimentary basin, maximum horizontal acceleration at PTN was 0.15g, 0.13g and 0.15g for NS, EW and vertical components respectively (Takai et al. 2016). The response spectra show the typical features. At rock site KTP, strong shaking was at 0.1 to 0.3 s, whereas for soil site at PTN strong shaking was at 3 to 5 s, which shows strong amplification of the lethal wave at longer period (Figure 3).

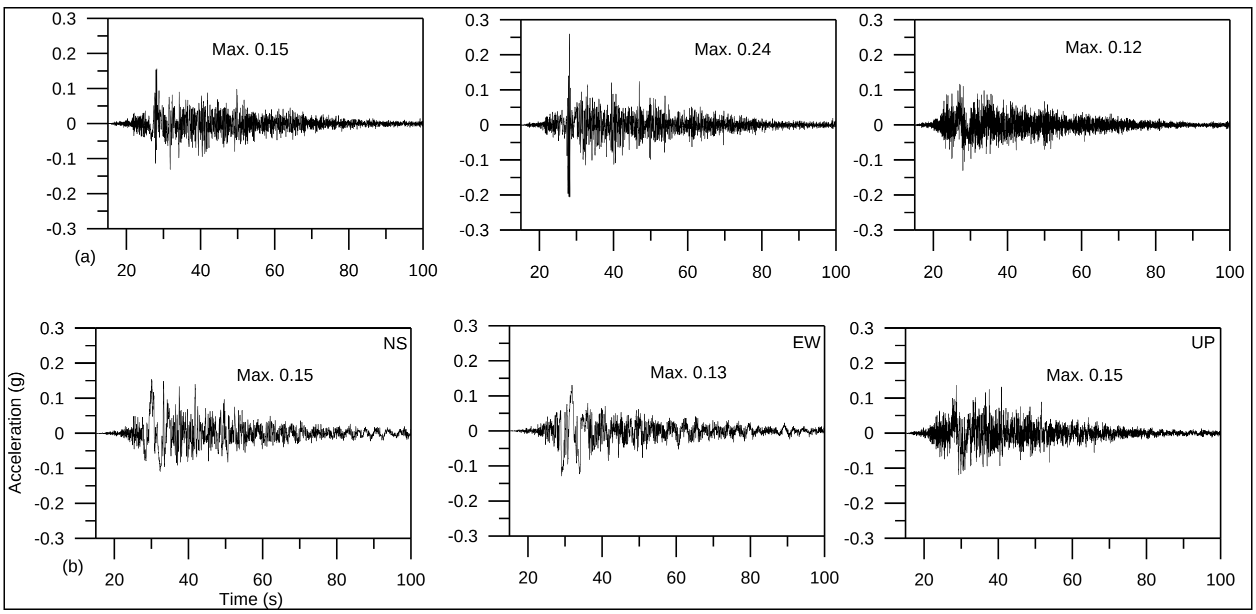

Figure 1. Acceleration time history of the main shock of the Gorkha earthquake measured at (a) Kirtipur, KTP, rock site (b) Pulchok, PTN, soil site (Reproduced with permission from Takai etal. 2016)

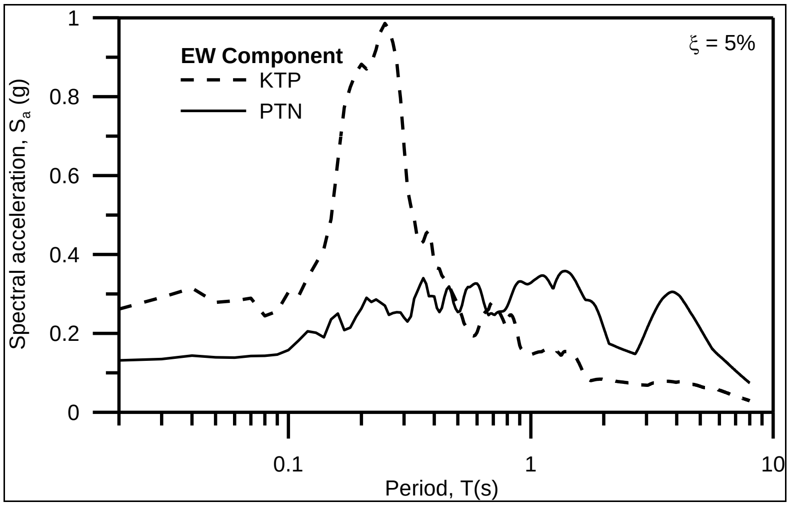

Figure 2. Response spectra of measured ground motion at KTP and PTN.

1.3 Ground Response Analysis

1.3.1 Methodology

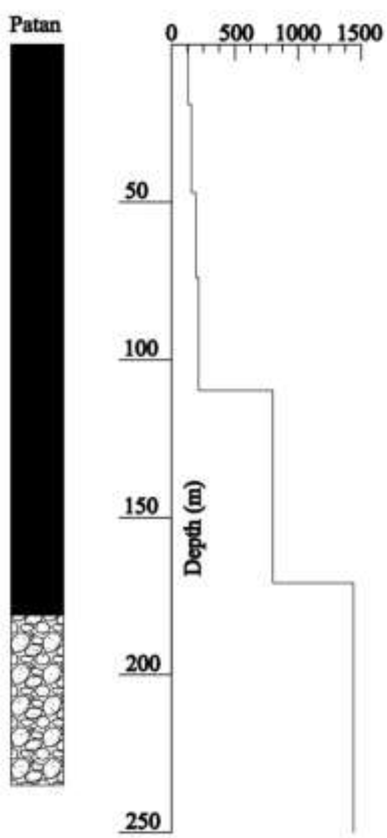

Figure 3. Geotechnical model for bore hole at Patan with shear wave velocity. The upper black layer is clay and lower is gravely sand.

Ground response analysis has been performed using DEEPSOIL code. It is a unified 1D equivalent linear and nonlinear site response analysis platform. It has features like strength controlled non-linear model, frequency-independent damping formulation and generation and dissipation of pore water pressure. The 1-D time domain analyses were performed by using a Newmark (1959) method to solve the dynamic equations of the motion on a lumped mass scheme.

1.3.2 Database

The study is based on both primary and secondary data. The primary data includes shear wave velocity obtained from the microtremor survey; whereas secondary data consist of collection of borehole litholog data. A borehole log at Patan is used to assess the site effects in the valley due to the Gorkha earthquake. The velocity structure was obtained through the Centerless Circular Array (CCA) (Cho et al. 2006) microtremor survey technique. This technique is based on the uses of the record of microtremor in vertical component to determine the relationship between the temporal and spatial spectra of waves and obtain phase velocity dispersion curve. Using the dispersion relations of phase velocity and frequency, a shear wave velocity was computed using technique of Yokoi (2009).

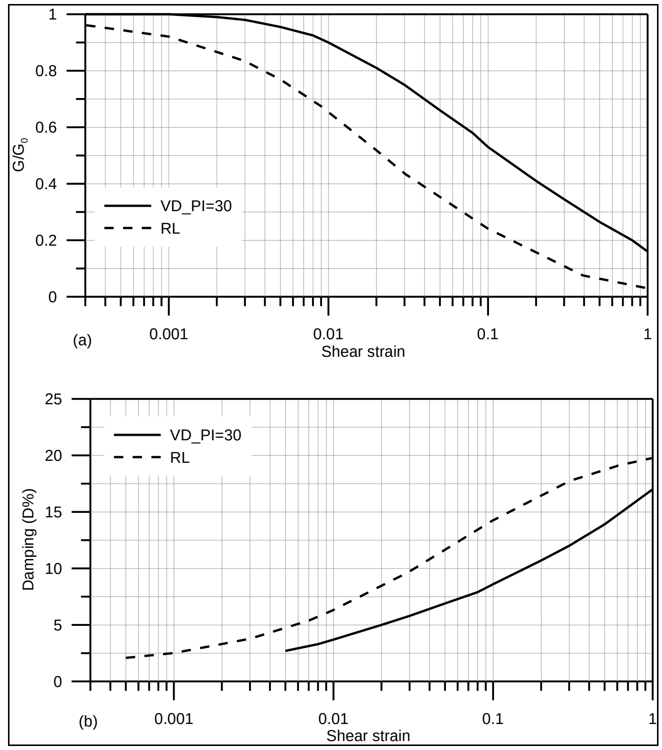

Figure 5. Soil curves used for computation. Reproduced with permission from Vucetic and Dobry (1991); Rollins et al. (1998)

1.3.3 Geotechnical Model

For the analysis, a geotechnical model is prepared for the borehole log of Patan. The borehole log at Patan with 235 m soil profile contains 179 m clay on top, which overlays the 56 m gravelly sand (Figure 4). The soil profile and corresponding shear wave velocity is also shown in Figure 4. Near the Patan, the shear wave velocity at 30 m depth is 156 m/s. The plasticity index of fine grained in the area is found to be varying in between 0 to 30 (Kattel et al., 1996). In the soil model of 30 has been used for clay. In the absence of the dynamic properties of the soils in Kathmandu Valley, for modeling purpose, the experimental curves proposed by different researches (e.g. Vucetic and Dobry, 1991; Rollins, 1991) have been used (Figure 5). The PI based curves proposed by Vucetic and Dobry (1991) have been used for fine grained soil. Similarly, for gravelly soil, curve proposed by Rollins (1991) was sed. For geotechnical characterization, shear wave velocities obtained from microtremor survey were used to prepare the 1D model

(Figure 4). The EW component of ground motion of Gorkha earthquake measured at KTP was used as the input motion.

2. RESULTS

The results of this study are presented in the form of site-specific response spectra and spatial distribution of computed ground motion parameters throughout the KMC.

2.1 Site Specific Response Spectra

The site-specific response spectra have been produced for Patan. The bore hole at Patan is located at the Lalitpur Metropolitan City (LMC) and is very close to the accelerometric station at soil site, i.e. PTN. The comparison of the measured ground motions at PTN and KTP has shown strong deamplification of the PGA value and modification of the response spectra (Figure 6). The equivalent linear analysis has given the similar shape of the response spectra with lower values of peak spectral acceleration. The computed PGA value is significantly higher (0.17g) than the measured one (0.13g). Strong shaking at the longer period has also been well captured at the longer period as shown by the measured data. In contrast, the non-linear analysis has revealed the consistent shape of the response spectra with slightly lower PGA as compared to the measured value. The analysis is able to capture the long period shaking revealed the measured data (Figure 6). The result shows strong deamplification of the PGA, long period shaking and able to capture the shape of response spectrum for measured ground motion.

3. RESULTS AND DISCUSSIONS

One-dimensional ground response analysis has been carried out for the single borehole log located in Patan, a central part of the intermontane basin filled up with fluvio-lacustrine sediments e.g. clay, silt, sand and gravel. Both equivalent linear and non-linear analyses were carried out to predict the ground motion in Patan. The long period ground motions with strong shaking at longer period was well computed using non-linear approach and significantly captured the characteristics of measured ground motions parameter in the soil site. The measured and computed ground motions have clearly shown the strong shaking in longer period that has caused significant damages to tall structures e.g. temples in Patan Durbar Square nearby study sites. Beyond this but within the valley Dharahara (Tower) was completely damaged and many high rise buildings were severely damaged.

Thus the modification of the waves due tolocal geology has played key role to damage pattern.

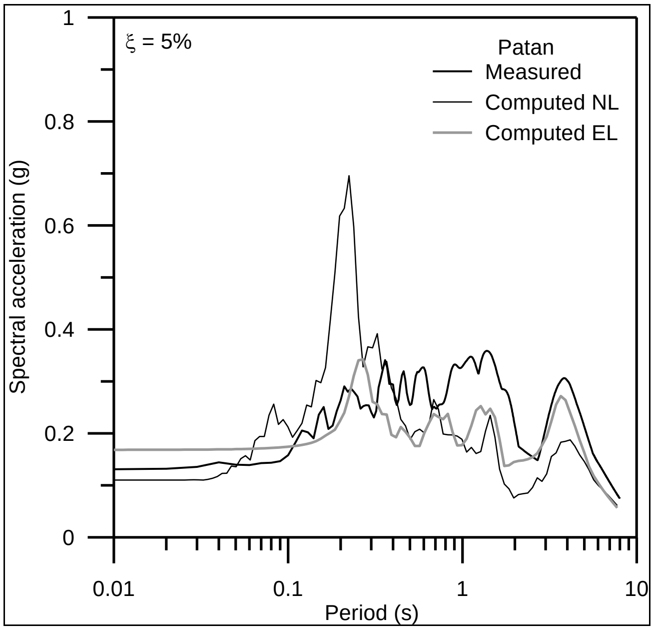

Figure 6. Response spectra for Patan.

In summary, observation of strong deamplification of PGA values in the soil sites compared to rock site (KTP), characteristics of the measured, computed ground motions, and few experiments on soil properties of Kathmandu Valley, a strong non-linear behavior of the soft sediments was found, which led to non-uniform damages during the 2015 Mw 7.8 Gorkha earthquake in the Kathmandu valley.

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