A study on shaking of tall buildings in Kathmandu Valley during the 2015 Nepal Earthquake

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ABSTRACT

Kathmandu Valley ground is a drained lake bottom made of soft soil deposition. In soft grounds, the resonance effect in ground and structures during earthquake vibrations plays an important role in intensifying the structural damage. In this study, ambient vibration of 33 taller buildings of varying height (i.e., 7 to 19 stories) in the valley was recorded after the 2015 Nepal Earthquake to understand the effect of resonance on building shaking. A comparison of the results of the ambient vibration data of the buildings and corresponding microtremor data of the ground points indicates that the predominant periods of about 60% buildings are close to the predominant periods of the ground, and those of about 25% tall buildings are nearly equal to those of the ground. This reveals that the ground-building resonance effect was the main cause of heavy shaking especially of the tall buildings in the Kathmandu Valley during the 2015 Nepal Earthquake.

Keywords: 2015 Nepal Earthquake; Kathmandu Valley; ambient vibration

1 INTRODUCTION

On 25 April 2015, Nepal was hit by an Mw7.8 earthquake, which killed about 9,000 people and destroyed hundreds of thousand houses and buildings across the country including many recently built reinforced concrete buildings in the capital Kathmandu. Kathmandu and its neighborhood areas are situated on a deeply-filled lake deposit, which is estimated to be 350 m to 600 m deep (e.g., Sakai et al. 2001; Moribayashi and Maruo 1980; Paudyal et al. 2013). The lacustrine deposit of the Kathmandu Valley is composed of interstratified layers of gravel, sand, silt, and clay with massive distribution of thick layers of organic clay material, especially in the middle and southern parts of the valley. Soft soil deposits of large thickness over the bedrock amplify earthquake motion as per its properties and frequency content in the waves. Such features of the Kathmandu Valley ground are often considered to lead to basin effect during earthquake motion, in which the ground shaking lasts for longer periods.

In the 2015 earthquake, the six strong ground motion recording stations in the Kathmandu Valley showed different records of ground shaking, especially in the center and in the peripheral areas of the valley (Bhattarai et al. 2015; Takai et al. 2016, etc.). The variation in ground response is due to the depth and properties of sediment deposit at each station point, so various locations in the Kathmandu valley ground might have experienced different frequency shakings. According to Paudyal et al. (2012), the predominant frequency in the central part of the Kathmandu Valley varies from 0.3 Hz to 0.488 Hz, which reflects the velocity contract of the deep sedimentary basin. According to Takai et al. (2016), the horizontal long-period oscillations on the sedimentary sites had enough destructive power to damage high-rise buildings with natural period of 3 s to 5 s.

During the 2015 earthquake, the recorded earthquake motion in terms of peak ground acceleration was well below 200 cm/s^2 (or gal) (Takai et al. 2016; Bhattarai et al. 2015; etc.), while the ground shaking lasted for about 60 seconds, which led to massive damage of not only the non-engineered masonry buildings and poorly engineered short-height reinforced concrete buildings but also comparatively well designed tall reinforced concrete buildings (Fig. 1) constructed on raft foundations. The tall buildings were shaken and heavily damaged all throughout the valley while the short-height buildings were affected in some pocket areas, particularly in the outskirts of the valley. The trend and extent of damage to the building structures in the valley during the 2015 earthquake indicates that there is a significant effect of site-specific properties of the ground, particular due to distribution of soft clay deposits and depth of the valley sediment. Some researchers (e.g., Dixit et al. 1998; Gautam and Chaulagain 2016; etc.) have studied earthquake vulnerability of residential buildings in the valley, but no such work has so far been done for recently constructed tall apartment and commercial buildings in the valley.

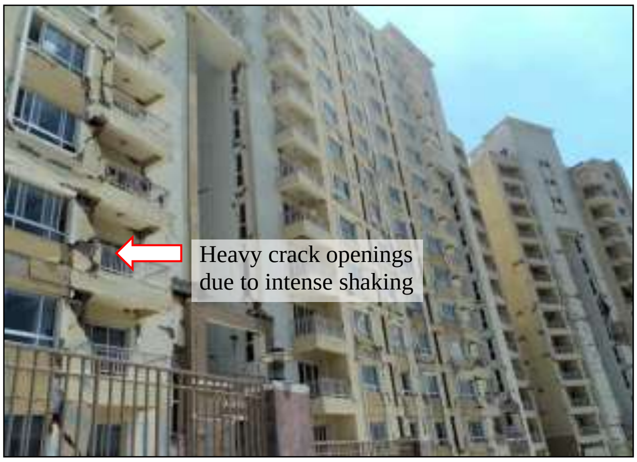

Fig. 1. A typical damage scenario of a 17-story apartment building (Location no. 22 in Fig. 2) on raft foundation in the Kathmandu Valley.

In this work, we recorded ambient vibration of 33 tall buildings and microtremors at the corresponding ground points in different locations of the Kathmandu Valley, as indicated in Fig. 2. The target buildings range in height from 7 to 19 stories. The recorded vibration data were analyzed using Floor-Spectral-Ratio (FSR) technique (Herak 2011) to derive predominant frequency and period of each building. The predominant periods obtained for the tall buildings were compared with those obtained for the nearby free-fields (i.e., corresponding ground points) to assess ground-structure frequency resonance effect on the tall building shaking during the 2015 Nepal Earthquake.

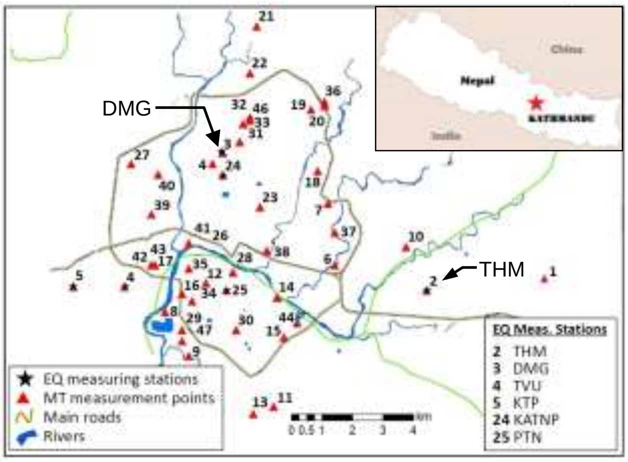

Fig. 2. Target tall building locations and the earthquake strong motion measurement points in the Kathmandu Valley.

2 MATERIAL AND METHOD

The ambient vibration of the tall buildings and microtremors at nearby free-fields were recorded using a portable velocity sensor, NewPic (SDR Co. Ltd.), at the 33 tall-building locations in the valley (Fig. 2). The velocity sensor used can measure three components: two horizontal components in east-west (longitudinal direction for the building) and north-south (transverse direction for the building) directions and one in vertical direction.

While doing the measurements, the device was placed near or at the center of mass of the building or close to the wall of the central column. Free-field measurement was done near the building, but far enough to avoid any influence of movement of the target building, nearby buildings and trees, or any other sources of unwanted noise. At each measurement point, the data recording was done for 300 seconds (i.e., 30,000 samples at a sampling rate of 100 Hz).

In analysis stage, each component of the signal was corrected by base line correction method so as to avoid any unwanted noise from other sources, and divided into 15 windows of 2048 data samples each (i.e., 20.48 s data in one window). For each measurement point, 7-12 windows were picked up for analysis omitting the windows that were seemingly influenced by nearby unwanted noise sources. Then, the Fourier analyses of the data in each window were performed, and the obtained spectra were smoothed by Parzen window of 0.5 Hz bandwidth. The transfer function of the building was estimated by taking a ratio of spectrum of the building to that of the free-field (or the ground point), which is known as the Floor-Spectral-Ratio (FSR) (Herak 2011), while the transfer function of the ground was estimated by taking a ratio of horizontal to vertical spectra of the ground, which is commonly known as the Horizontal-to-Vertical Spectral Ratio (HVSR) (Nakamura 1989). After obtaining the transfer functions for all windows, an average was obtained as the FSRs and HVSRs for all buildings and free-fields respectively. The frequency corresponding to the first peak of the FSR and HVSR plot is designated as the fundamental frequency of the building and the corresponding ground respectively.

3 RESULTS AND DISCUSSION

Typical results for a 10-story building and its free-field in terms of Floor-Spectral-Ratio (H/H) and Horizontal-to-Vertical (H/V) spectral ratio respectively are presented in Fig. 3. The fundamental period of this 10-story building is 1.25 s in longitudinal direction (X-axis) and 1.47 s in transverse direction (Y-axis) while it is about 0.89 s for the free-field.

The results of the ambient vibration survey reveal that the fundamental periods of the 7- to 19-story buildings in the valley range from 0.34 s to 1.92 s. The results of the variation of the fundamental period of the buildings and the free field motion are summarized in Fig. 4. The fundamental periods for the building no. 2, 3, 9, 13, 19, 22, 28, and 31 are quite close to the predominant periods of corresponding free-field vibrations. This generally means the possibility of ground-building resonance effect is very high for these buildings during earthquake shakings. Similarly, the fundamental periods of the building no. 6, 8, 11, 12, 16, 21, 24, 29, 30, and 32 are nearly close to the predominant period of the corresponding free-filed motions, while for the building no. 1, 5, 7, 17, 18, 23, 25, 26, 27, and 33, they are slightly apart. As a whole, the fundamental periods of about 60% of the target tall buildings were found to be close to the predominant periods of the corresponding ground while about 25% of the buildings were found to have their fundamental periods almost equal to the predominant periods of the corresponding ground.

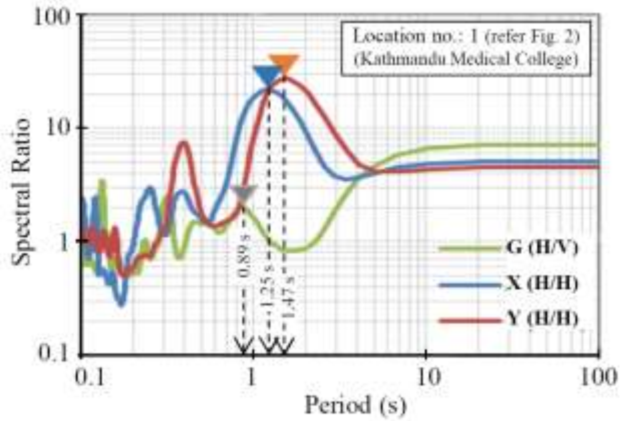

Fig. 3. Spectral ratio vs period graph for a 10-story building [G (H/V): horizontal-to-vertical spectral ratio for the free-field; X (H/H): floor-spectral ratio for building in longitudinal direction; Y (H/H): floor-spectral ratio for building in transverse direction].

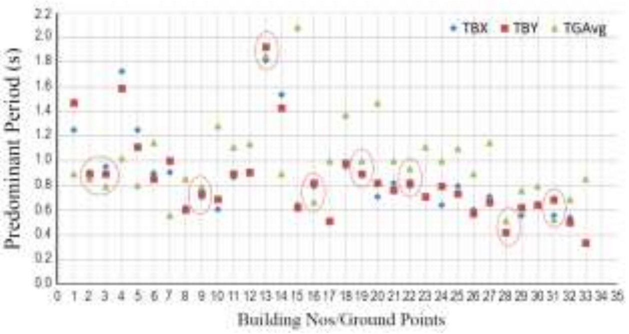

Fig. 4. Comparison of fundamental periods of the target buildings and predominant periods of nearby free-field [TBX: fundamental period of the buildings in longitudinal direction; TBY: fundamental period of the buildings in transverse direction; TGAvg: average predominant period of the free-field].

Building no. 13, a 17-story building and building no. 28, a 7-story building were red-tagged (i.e., imminent danger of collapse during an aftershock, unsafe for occupancy or entry except for the government authorities, and significant threat to life safety) by the government authorities during the damage assessment. These two buildings are found to have their fundamental periods almost the same as predominant periods of the ground points. So, the above results reveal that the ground-building resonance effect is one of the major causes of intense shaking and resulted heavy damage of most tall buildings in the Kathmandu Valley during the 2015 Nepal Earthquake.

According to Takai et al. (2016), during the 2015 earthquake, the earthquake motion recorded in the Kathmandu Valley was found to be different at each station, and the recorded peak ground accelerations (PGA) at all points were comparatively low (i.e., below 200 cm/s^2) while the earthquake shaking lasted for about 60 s. The ground vibration patterns during strong motion and microtremors significantly differ, and it is often difficult to predict if the ground will vibrate with the same predominant frequency as estimated by the microtremor method. However, when the strong ground motion starts to dissipate and comes to a long duration low-amplitude vibration or when the ground is still in the phase of primary-wave vibration, the ground motion can be expected to behave in the similar way as in the effect of microtremors. So, in this study we also did a comparative analysis of ground motion patterns during the main shock of the 2015 earthquake low-amplitude strong motions (Fig. 5) at two representative strong motion recording stations, DMG and THM (refer Fig. 2 for location) for understanding similarities in ground vibration patterns during microtremors and strong motion dissipation stage.

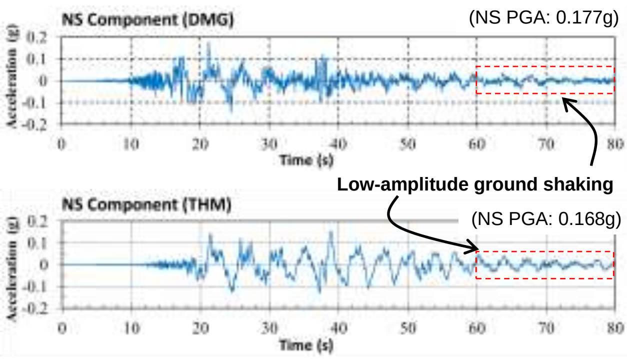

Fig. 5. Typical waveforms of N-S direction recorded during the 2015 Nepal Earthquake at two strong motion recording stations, DMG and THM, and the low-amplitude ground vibration stage after about 60 s from the start of the record.

The results of the above comparative analysis are presented in terms of H/V spectral ratio in time domain in Fig. 6. It is quite clear from this figure that the predominant periods of the ground points estimated by microtremor method are very close to the dominant periods of shaking during the dissipated strong motion, especially after 60 s from the start of data recording. This is evident to the fact that during the strong motion energy dissipation and in the stage of low-amplitude shaking, the ground vibrates with the similar pattern as in case of microtremors, which may cause intense resonance effect in the building or structural shaking even during the long-duration low-amplitude motion.

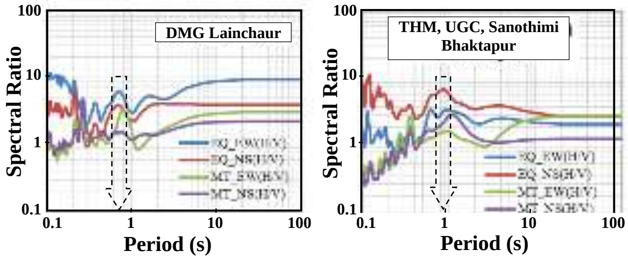

Fig. 6. Comparison of low-amplitude ground motion characteristics during the main shock of the 2015 earthquake with that in microtremors at DMG and THM stations [EQ: earthquake; MT: microtremor; EW: east-west component; NS: north-south component]

Finally, through this work, it is understood that the shaking pattern of deep lacustrine deposits as in the Kathmandu basin may result in ground-structure resonance effect even during low intensity earthquakes leading to intense shaking of long period structures such as tall buildings. The ambient vibration data and microtremor data analysis results reveal that the fundamental periods of most tall buildings in the Kathmandu Valley are close to the predominant periods of the corresponding ground. Consequently, the tall buildings might have experienced ground-structure resonance effect during the 2015 earthquake, especially after the earthquake energy started dissipating largely.

4 CONCLUDING REMARKS

This paper has attempted to address the issue of vulnerability of tall buildings in the Kathmandu Valley and similar ground structures during earthquakes. The recent 2015 Nepal Earthquake caused intense shaking of all tall buildings in the valley and partially damaged many of them. In this work, ambient vibration and microtremor survey methods were used to assess shaking properties of the existing tall buildings in the Kathmandu Valley and corresponding ground points at a total of 33 locations. The analysis showed that the predominant periods for the measured 7 to 19 story buildings range from 0.34 s to 1.82 s. Of the total measured tall buildings, 60% were found to have their fundamental periods very close to the predominant periods of the corresponding ground points, and about 25% were found to have their fundamental periods nearly equal to the predominant periods of the ground points. These estimated natural periods of the buildings and the corresponding ground reveal that a part of the tall buildings in the valley underwent massive frequency resonance during the 2015 Nepal Earthquake leading to intense shaking and significant damage.

Moreover, a comparative analysis of the ground vibration pattern at two strong motion recording stations in the valley during the microtremor measurement and during the stage of low-amplitude ground vibration after the 2015 earthquake strong motion dissipation revealed that the estimated predominant periods of the ground points were quite close. This probably makes it clear that the tall buildings were resonantly shaken during the phase of strong motion energy dissipation.

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