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USE OF AMBIENT VIBRATION METHODS FOR POST-EARTHQUAKE GEOTECHNICAL RECONNAISSANCE IN KATHMANDU, NEPAL

S. Molnar[(1)], J. Onwuemeka[(2)], and S. Adhikari[(3)]

[(1)] *Assistant Professor, University of Western Ontario, Dept. Earth Sciences, London, ON, smolnar8@uwo.ca*
[(2)] *Course-based M.Sc. student, University of Western Ontario, Dept. Earth Sciences, London, ON, jonwueme@uwo.ca*
[(3)] *Geologist, NSET, Urban Disaster Risk Management, sadhikari@nset.org.np*

Abstract

The Canadian Association of Earthquake Engineering sent a seven member team to Kathmandu, Nepal, following the 2015 M7.8 Gorkha earthquake. The M7.8 Gorkha earthquake of 25 April 2015 resulted in ~8800 fatalities and structural damage of ~600,000 buildings. A set of five small Tromino seismographs were brought to Nepal to obtain a crude reconnaissance of potential earthquake site response across Kathmandu. Individual sensor measurements were conducted in several locations across Kathmandu – in locations of minimal to heavy structural damage. Microtremor horizontal-to-vertical spectral ratios (MHVSR) are computed for each individual measurement to obtain an estimate of site period (fundamental frequency) of the subsurface soils. Three groupings of MHVSR response are observed: (1) moderate-to-high amplification at distinct frequencies occurs in locations of heavy structural damage or collapse, (2) low, broad amplification is observed in locations with minimal structural damage, and (3) moderate amplification at high frequencies is observed atop topographic hills and/or rock sites. All five Tromino sensors were also deployed, together as an array, in select locations of Kathmandu for measurement of surface wave dispersion. This paper presents application of surface seismic field techniques for post-earthquake geotechnical reconnaissance purposes in Kathmandu, Nepal.

Keywords: seismic microzonation, microtremors, amplification, earthquake site class.

1. Introduction

Active convergence of the continental Indian plate into the continental Eurasian plate (30-40 cm/year) has resulted in the highest elevated mountains, the Himalayas, in the world. Crustal shortening is accommodated by major thrust faults that strike east-west across Nepal. From south to north these major thrust faults are: main frontal, main boundary, and main central thrust faults, which are splay faults of the main Himalayan thrust fault between the two tectonic plates at depth.

Ten or more 'great' earthquakes, i.e., magnitude (M) 8 or greater, are known to have occurred along the Himalayan thrust zone from paleoseismic studies and historical records. Kathmandu has been significantly damaged by past great earthquakes (M 7.5 to 8.4) in the years 1255, 1344, 1408, 1681, 1833, and 1934 [1]. The last great earthquake in 1934, occurred immediately east of Kathmandu resulting in ~10,000 fatalities. Recorded seismicity has demonstrated that the major shallow thrust faults are generally quiescent with earthquakes occurring in the overriding Eurasian plate (≤ 20 km depth) as a band of seismicity in the lesser Himalayas [2]. Deeper earthquakes occur at the base of the Indian plate (or top of the Moho) at 40 km depth at the collisional interface and at 80 km depth beneath the Himalayas [3]. Hence, the main Himalayan thrust fault is currently locked and generates great M ~8 earthquakes at a recurrence interval of ~100's of years.

2. The 2015 Gorkha, Nepal, earthquakes

From an examination of the areas and dates of past great earthquakes, and review of their past damage [4], a future great earthquake is expected to occur very near to Kathmandu, resulting in a catastrophe due to the combination of very high earthquake shaking and significant exposure of vulnerable buildings and population. The 25 April 2015 M 7.8 Gorkha mega-thrust earthquake therefore occurred in an anticipated location, 80 km NW of Kathmandu at a depth of 15 km, yet all other seismological considerations defied expectations. The shaking intensities and resulting damage in Kathmandu were generally lower than expected resulting from the culmination of lower than expected magnitude, source frequency content, and blind-thrust rupture (i.e., rupture stopped at depth).

Inversions of worldwide seismic data (USGS and IRIS moment tensor solutions) demonstrated that the M 7.8 Gorkha earthquake is a thrust faulting event striking northwest-west with a shallow (7-10^0) dip. The M 7.8 Gorkha earthquake was the first large continental megathrust rupture to have occurred beneath a high-rate (5-Hz) Global Positioning System (GPS) network [1]. Rupture propagated unilaterally as a single ~6-sec duration pulse, predominantly eastward (along strike) and slightly southward at ~3 km/sec, taking ~35-sec for the first seismic P-waves to reach Kathmandu, and rupturing a full 150 km distance. Rupture also propagated slightly downdip. Slip was concentrated north of, and at 10-15 km depth beneath, Kathmandu; maximum slip of ~6 m occurred east of Kathmandu [1, 5]. The Kathmandu valley rebounded upwards by ~1.0-1.5 m and south by ~2 m. Aftershocks highlight the mainshock rupture area. A second major event occurred on 12 May 2015 with a moment magnitude of 7.3, located at the eastern edge of the mainshock rupture zone.

Few strong-motion instruments were operating in Nepal at the time of the Gorkha earthquake. Mainshock peak ground acceleration (PGA) values at two strong-motion stations operating in central Kathmandu are: 0.16 g (USGS KATNP station; [6]) and 0.18 g (NSC DMG station; [7]). For the M 7.3 largest aftershock, PGA values are 0.087 g (KATNP) and 0.12 g (DMG). In the deep lacustrine sediment Kathmandu valley, the frequency content of the mainshock is predominantly 0.2-0.25 Hz (4-5 seconds), with site amplification occurring at 0.25-0.3 Hz (3-4 seconds) [1]. Higher frequency ground motions were generated by the mainshock north of Kathmandu, and by aftershocks (3-5 Hz) in Kathmandu.

3. Observations – Damage and Ground Motion Intensities

Figure 1 shows locations visited by the CAEE reconnaissance team (red pushpins) and corresponding images of observed damage and ground motion intensity. Table 1 summarizes locations visited in and around Kathmandu during the 10-day CAEE reconnaissance mission and associated observations. The CAEE team provided oral presentations of preliminary findings to ~150 Nepalese government officials (June 15th), and attended a European-Nepalese (ITCP-NAST) academic workshop in Kathmandu (June 17th).

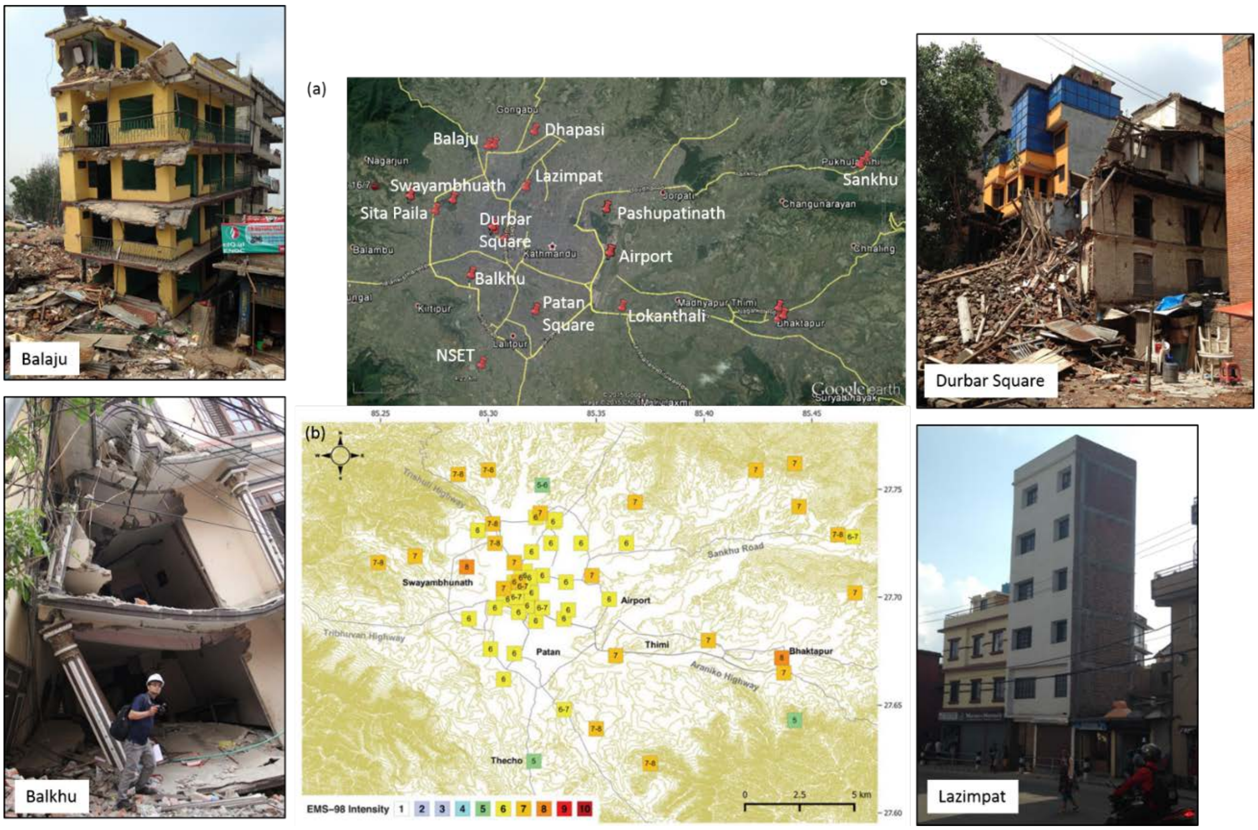

Figure 1. (a) Sites visited in and around central Kathmandu by the CAEE reconnaissance team marked by red pushpins. (b) Macroseismic EMS-98 intensity map of the M 7.8 Gorkha earthquake [8]; Fig. 2.

Table 1. Summary of locations visited by the CAEE reconnaissance team and associated observations.

Date	Location	Description and summarized observations
June 10	NSET, southern Kathmandu	Meeting at NSET with Nepalese collaborators. Minimal observed damage of residential buildings (cracks in walls) in neighbourhood.
	Balkhu, SW Kathmandu	Several collapsed buildings in neighbourhood. One building with collapsed upper floor. Several homes are significantly damaged.
June 11	Balaju, NW Kathmandu	West of Bishnubati bridge. Site comprised of four mid-rise 'guest houses' – two collapsed, third is leaning (lowest floor collapsed), with the fourth still upright and without observed damage. Ground is depressed (~2-m max. lower) than ring roadway but not sloping. Presence of soft clay lined holding ponds, 50-m behind buildings. ~75 fatalities.
	Gungabu, NW Kathmandu	East of Bishnubati bridge. Pocket of collapsed buildings within 'city block'. First floor of one building collapsed; building fell forward, now leaning on another building. Active deconstruction occurring. Pancaked school in neighbourhood.

	Dhapasi, northern Kathmandu	Clay hill (~30-50 m) with recent complex of high-rise (17 storey) apartment buildings. Spalling of walls; X-pattern cracking observed in the lower 8 floors. Excavation (~two floors) for underground parking.
	Sankhu village, ~15 km NE of Kathmandu	Across main road from Kathmandu, no observed damage of NSET retro-fitted school. Walk into the village: ~80% of buildings have collapsed. Dichotomy between primarily old masonry (collapsed) buildings and few recent concrete-frame (standing) buildings. Some streets still thick with rubble, some cleared. People living in tents, deconstructing, washing from water taps. One bulldozer.
June 12	Bhaktapur, ~12 km east of Kathmandu	UNESCO world heritage site - Main (Durbar) square cleared and large heritage temples still standing (minimal damage), but every alleyway leading outward from square is full of rubble.
	Lokanthali, ~30 km east of Kathmandu	Differential settlement of highway; spans depressed ground (filled river channel; no surface water). Tilting (3°) of surrounding buildings with ~30-cm offsets; cracks in walls and roadway. See Fig. 6 in [9].
	Sita Paila, west Kathmandu	Two collapsed concrete buildings along ring road. Active deconstruction; hammering of bricks and concrete to strip out steel.
June 13	Dolakha district, ~75 km east of Kathmandu	Ten-hour round-trip drive to Dolakha district. Observe landslides, sections of highway cleared from debris, collapse of masonry homes. Meeting with district mayor; April earthquake not as damaging (5 fatalities) as May aftershock (2 km away). People sleeping outside, so low aftershock fatalities (1). District has 31,000 people and 7,000 buildings requiring reconstruction. Quick reconnaissance of 'old city'; terraced hillslopes and masonry 1-2 storey homes with damaged walls.
June 14	Airport, eastern Kathmandu	Microtremor testing at Kathmandu airport. Fuel tanks are ~8-m high; report of some spillage from sloshing. No cracks or offsets. No significant damage to airport runway; operating.
June 16	Swayambhuath hill, western Kathmandu	"Monkey Temple"; ~100-m rock outcrop. One of two circular shika's (free-standing column) fell 'backwards' towards stupa and 'away' from steep front of hill. Significant damage to monastery masonry buildings; women are carrying debris downhill in baskets on their backs.
	Patan, southern Kathmandu	Main Durbar square still closed. Walked around outer palace square. Temples or pagodas are generally still standing, minimal damage with wooden supports.
	Pashnupatinath, NE Kathmandu	No damage observed at sewage treatment facility.
June 18	Sindhupalchuk district, ~40 km NE of Kathmandu	Drive to Sindhupalchuk district; stopping at several ridge-top road-side villages. Generally tallest buildings built along main road with commercial soft-storey on sloping ground, which are leaning or collapsed (foundations on non-uniform ground). Commercial spaces are operating during day even in red-tagged or damaged buildings (merchants sleep in tents overnight). There are a few glass-front buildings with unbroken windows – suggests low shaking intensity.
June 19	Sita Paila, western Kathmandu	Differential settlement in residential complex beside creek. Most homes with minimal damage, few with significant damage (~2-cm shifting of foundation, large cracks in walls). Homes closest to creek on terraced mud. Concrete from homes is poor quality, easily breaks in hand.
June 20	Central Kathmandu	Dharahara Tower area - observer described tower swayed north-south twice then east-west at which point it collapsed eastward. Down the street (~50-m north), out-of-plane wall failure at coin mint factory in same eastward direction as tower. Durbar Square area - again, some buildings have collapsed, while glass-front buildings are unbroken (low intensity?). Palace is significantly damaged (cracks and fallen bricks), but pagoda temples minimally damaged (wooden supports). Open to public and generally cleared of debris.

3. Potential Site Effects

Kathmandu is situated on a 500-600 m deep fluvio-lacustrine sedimentary basin underlain by metamorphic bedrock [1]. Microtremor (ambient vibrations) were performed in select locations in and around Kathmandu using ultra-portable three-component sensitive seismic sensors, called Trominos® (Figure 2). The Tromino is placed on the ground surface and a minimum of ~10 minutes of microtremors are recorded and the average horizontal-to-vertical spectral ratio (HVSR) is calculated. The microtremor amplification spectra are indicative of underlying ground conditions; a single clear peak indicates a significant impedance contrast.

Three distinct "groups" of microtremor amplification spectra (HVSR response) are apparent in Figure 3:

a) Low amplification with generally broad single peak response is observed at locations without reported damage in central (Lazimpat), southern (NSET), and eastern (Airport, Sewage Plant) Kathmandu. The HVSR response recorded at Lokanthali (highway settlement) is more similar to these non-damaged building sites in Kathmandu.

b) Distinct narrow single HVSR peaks with moderate to high amplification (factor of ~3-5) are determined at sites with significant observed damage in Kathmandu. A relatively high peak frequency of ~0.8-1.0 Hz is associated with sites in western Kathmandu in the Balagu-Gungabu area in the northwest, Sita Paila in the central west, and Balkhu in the southwest. In contrast, relatively low and broad amplification is determined at Dhapasi (damaged high-rise apartment complex).

c) Flat response (no amplification) is observed at terraced rock sites in Charikot, Dolhaka district (~75 km NE of Kathmandu; ~2500 m elevation), whereas broad amplification between 2-10 Hz is observed atop Swayambhuath hill (~100-m rock outcrop) likely due to near-surface jointing, fracturing, etc.

d) Similar to (b), distinct narrow single HVSR peaks with moderate to high amplification (factor of ~3-5) are determined at heritage sites in and outside of Kathmandu. The lowest peak frequency response (~0.3 Hz) is observed at sites in central Kathmandu, at or in the immediate vicinity of Durbar square and Dharahara Tower; Patan square to the south exhibits ~0.4 Hz response. In the Bhaktapur area, ~0.5 Hz peak response is observed. In Sankhu village, the relatively high frequency response (~1.0-1.2 Hz) is similar to significant building damage in western Kathmandu.

Figure 2. Photos of microtremor measurements performed in and around Kathmandu using ultra-portable TROMINO® sensors.

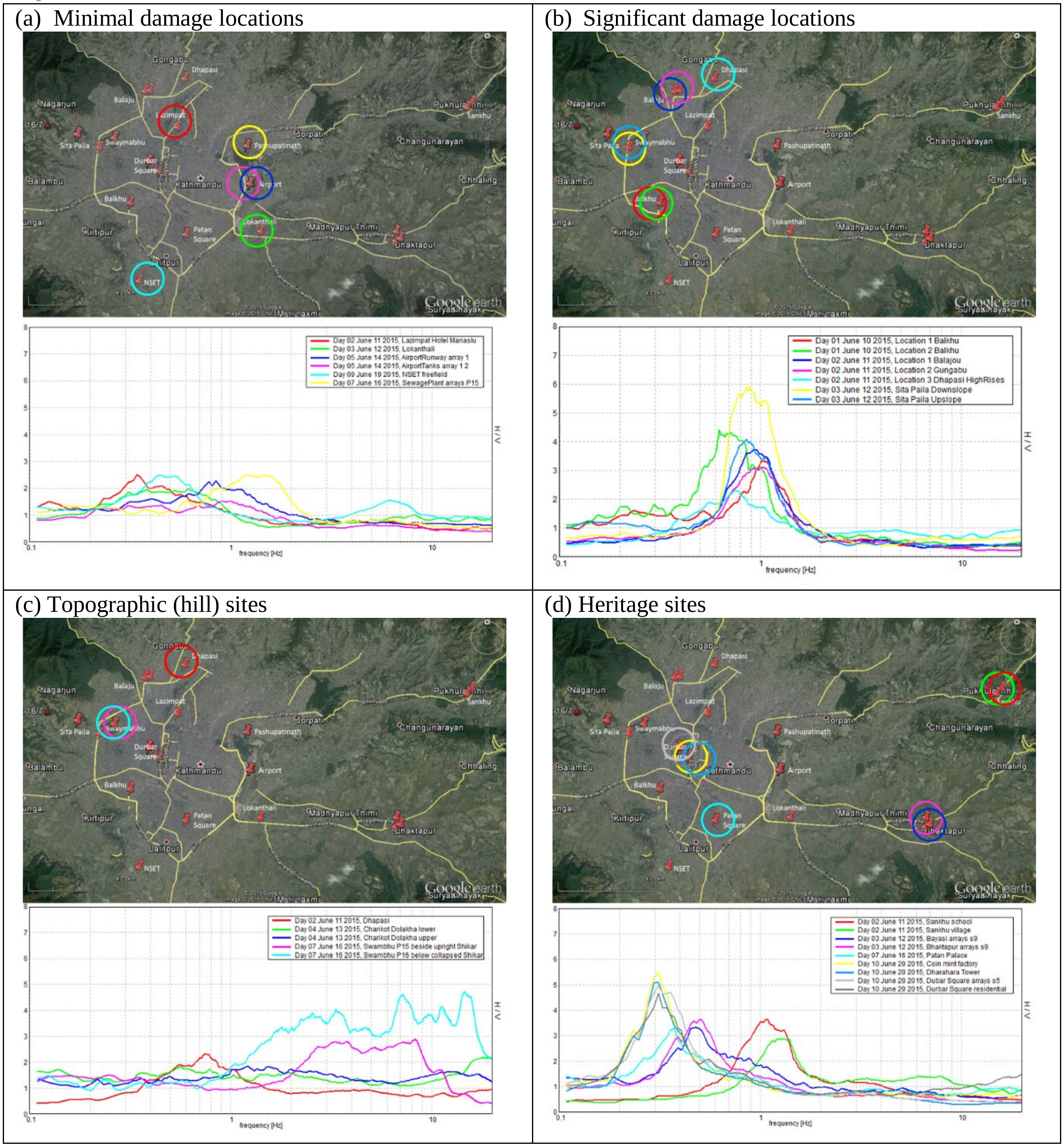

Figure 3. Microtremor HVSR response (amplification vs. frequency) measured in locations (a) of minimal and (b) significant observed damage in Kathmandu, as well as (c) at topographic hill and (d) heritage sites around Kathmandu. Colour corresponds to circled locations shown in maps above each plot.

Microtemor HVSR observations shown in Figure 3 are largely consistent with previous microtremor HVSR observations [10, 11], in particular Figure 7 in [11]. These previous investigations included a total of 172 microtremor HVSR measurements accomplished in a 1-km grid spacing, covering ~200 km^2 of the Kathmandu Valley.

4. Site Characterization

Seismic arrays or multiple seismic sensors allow retrieval of surface wave dispersion; surface wave phase velocities at particular frequencies. Surface waves disperse; long wavelengths sample deeper and generally higher velocity material than short wavelengths that sample near-surface lower velocity material. Hence, a dispersion curve typically exhibits high phase velocities at low frequency and low phase velocities at high frequencies. Models of subsurface stiffness or velocity depth profiles can be obtained from inversion of a site's measured dispersion characteristics.

Thickness of stratigraphic units in the 25 km by 20 km Kathmandu Valley are relatively known from ~500 drilled boreholes [11]. There are no publications documenting measured subsurface seismic velocities in the Kathmandu Valley; Bhandary et al. [11] report that standard penetration testing (SPT) has been accomplished. Therefore a rudimentary effort was made during the CAEE reconnassiance mission to perform surface wave dispersion measurements with the available 5 Tromino sensors at a handful of sites in the Kathmandu Valley. Rudimentary pertains to the low volume of available equipment, the available seismic source (first author jumping up and down), and relatively small sized arrays (few personnel available to deploy sensors in conjunction with limited spatial area due to debris and justifiably curious-to-suspicious onlookers). Figure 4 shows photos of Tromino arrays at select sites in Kathmandu.

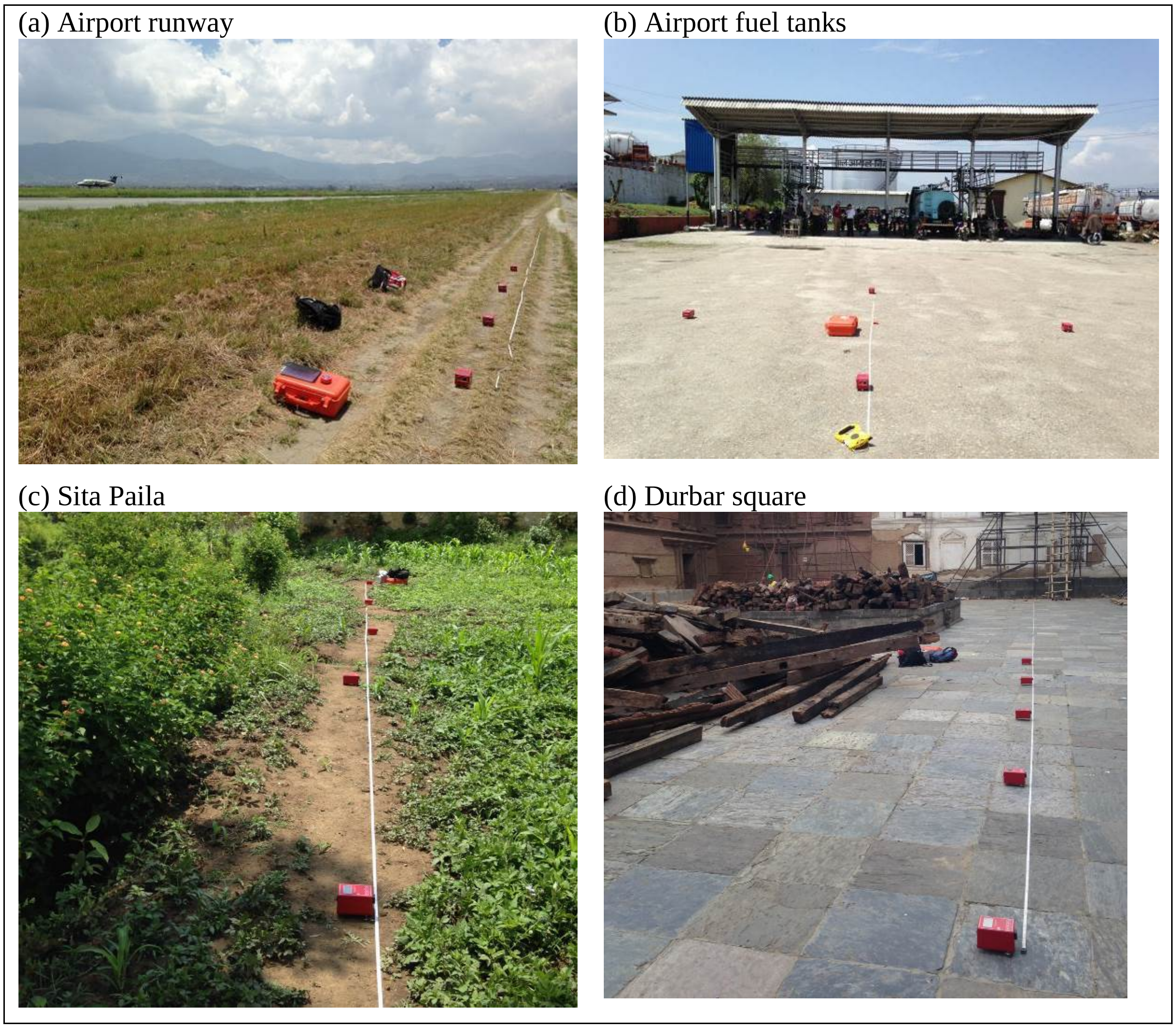

Figure 4. Photos of array measurements at selection locations in the Kathmandu Valley.

4.1 Preliminary results

Active-source surface wave methods were typically employed at all sites, known as multi-channel analysis of surface waves (MASW) method. Linear arrays of 4-5 Tromino sensors with sensor spacings of 1 m to 4-7 m maximum were generally accomplished at each site; total array lengths range between 16-28 m. Simultaneous recording duration was typically 5-10 minutes per array setup. A vertical seismic source, first author jumping, occurred at 5-m offset from each end of each linear array setup. Vertical component recordings were uploaded into a Geopsy database [12] and 1-sec time windows around the jumping source were extracted for dispersion analysis. Figure 5 shows the retrieved dispersion characteristics and preliminary manually-picked dispersion curves for three select sites in the Kathmandy Valley. Dispersion data are generally retrieved over the same high-frequency bandwidth (10-50 Hz) for all three sites related to the small sized arrays. All sites exhibit low phase velocities (< 250 m/s), indicating that near-surface materials are relatively soft.

Figure 5 also shows the average microtremor HVSR calculated at each sensor location for each array setup (coloured lines in left plots), which are averaged to determine an overall average microtremor HVSR for the site (black line with standard deviation limits shown as dashed lines). At each site, the microtremor HVSR response is generally consistent over the relatively small spatial area tested, providing confidence in similarity of subsurface conditions beneath the arrays. The peak frequency varies amongst the sites: 0.28 Hz at Durbar Square, 0.9 Hz at the airport runway, and 3.0 Hz in Sita Paila, indicative of greater depth to an impedance contrast in central Kathmandu than towards the east or west (i.e., expected sedimentary basin edges). Moderate peak amplification (~4) is observed at Durbar Square and Sita Paila in contrast to observed low amplification at the airport runway; hence, significant impedance contrasts are expected at Durbar Square and Sita Paila.

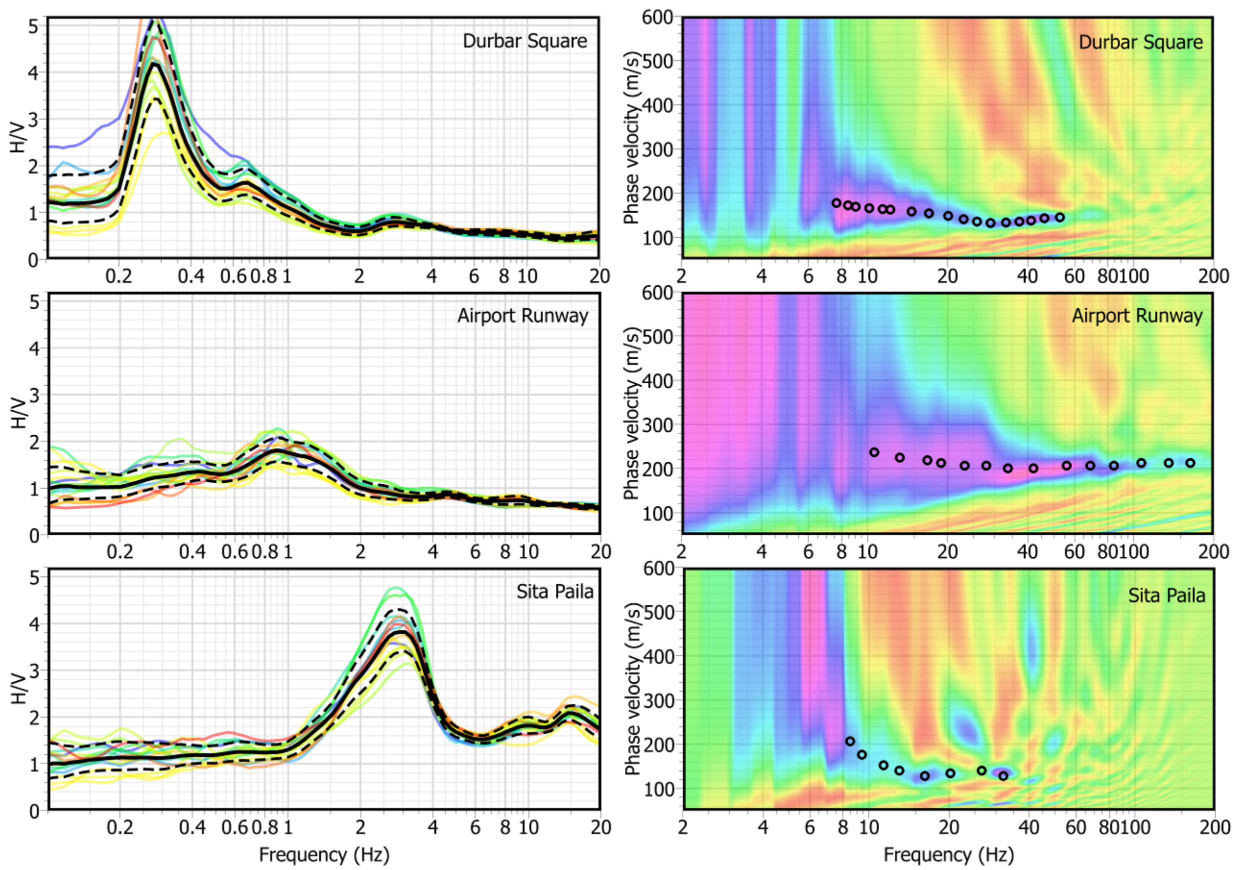

Figure 6. Average microtremor HVSRs (left) and dispersion curves (right) at three select locations in the Kathmandu Valley.

5. Summary

The Canadian Association of Earthquake Engineering sent a seven member team to Kathmandu, Nepal, following the 2015 M7.8 Gorkha earthquake. A set of five Tromino seismographs were brought to Nepal to obtain a crude reconnaissance of potential earthquake site response across Kathmandu. Four distinct forms of amplification response are observed in horizontal-to-vertical spectral ratios determined from the microtremor (ambient vibration) recordings. Three groupings of MHVSR response are observed: (1) moderate-to-high amplification at distinct frequencies occurs in locations of heavy structural damage or collapse, (2) low, broad amplification is observed in locations with minimal structural damage, and (3) moderate amplification at high frequencies is observed atop topographic hills and/or rock sites.

Preliminary site characterization at three sites in the Kathmandu Valley is presented (Figure 5). Slightly lower Rayleigh wave phase velocities (< 200 m/s) are determined at Durbar Square and Sita Paila sites in conjunction with moderate amplification over a relatively narrow frequency band; interestingly, these sites coincide with significant observed structural damage in the area (Palace, Dharahara tower and concrete high-rises, respectively). In contrast, the slightly stiffer and low broader amplification airport runway site coincides with no reported damage to the airport runway. Joint inversion of microtremor HVSR and final dispersion curves to obtain shear-wave velocity depth profiles will be accomplished for all investigated sites in future.

6. Acknowledgements

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