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ORIGINAL RESEARCH PAPER

Site amplification in the Kathmandu Valley during the 2015 M7.6 Gorkha, Nepal earthquake

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Abstract The 25th April 2015 **M**7.6 Gorkha earthquake caused significant damage to buildings and infrastructure in both Kathmandu and surrounding areas as well as triggering numerous, large landslides. This resulted in the loss of approximately 8600 lives. In order to learn how the impact of such events can be reduced on communities both in Nepal and elsewhere, the Earthquake Engineering Field Investigation Team (EEFIT) reconnaissance mission was undertaken, aiming to look at damage patterns within the country. Passive, microtremor recordings in severely damaged areas of the Kathmandu Valley, as well as at the main seismic recording station in Kathmandu (USGS station KATNP) are used to determined preliminary shear wave velocity (V_s) profiles for each site. These profiles are converted into spectral acceleration using the input motion of the Gorkha earthquake. The results are limited, but show clear site amplification within the Siddhitol Region. The resulting ground motions exceed the design levels from the Nepalese Building Codes, indicating the need for site-specific hazard analysis and for revision of the building code to address the effect of site amplification.

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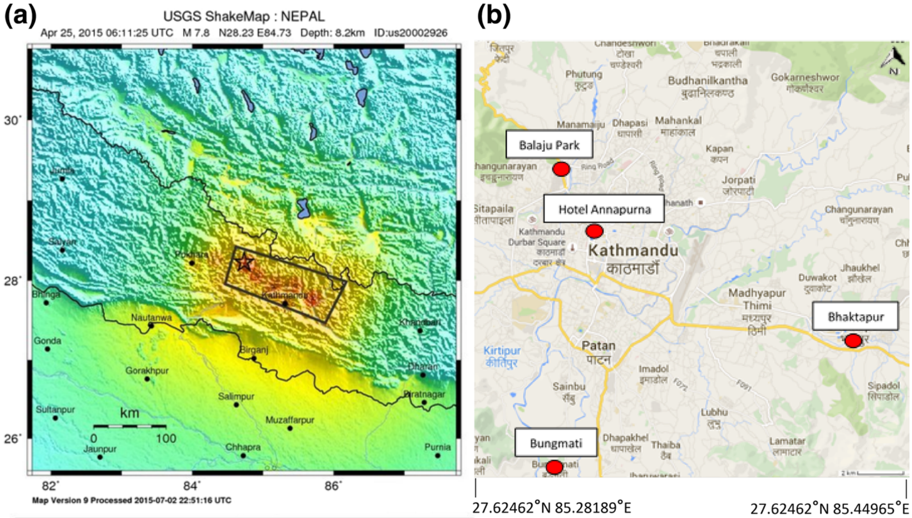
1 Introduction

The epicentre of the 25th April 2015, **M**7.6 Gorkha, Nepal earthquake was approximately 80 km north-west of Kathmandu, Fig. 1 (NSET 2015). With a shallow focus, only 15 km below the surface, this caused high intensity shaking, up to MMI IX (NSET 2015) in the epicentral zone, as well as triggering a considerable number of large landslides, within the northern half of the country. Devastation was widespread across Nepal, with at least 8600 fatalities and 16,800 officially reported injured (NSET 2015). The earthquake occurred at the end of the dry season and, therefore, further impacts during the monsoon season could be expected as the heavy rain acts on slopes weakened by the original shaking.

An Earthquake Engineering Field Investigation Team (EFFIT) was deployed to Nepal in June 2015, just in advance of the monsoon. The objective was to collect perishable data relevant to understanding the behaviour of buildings and infrastructure, as well as geotechnical failures and landslides (EEFIT 2015). EEFIT is a UK-based collaboration between industry and academia, to conduct field investigations in regions affected by major earthquakes. The main aim of this reconnaissance was to investigate the performance of structures, foundations, civil engineering works and industrial plants. Despite arriving over a month after the initial earthquake, aftershocks over **M**5.0 were still being experienced (NSET 2015).

Damage from recent earthquakes worldwide show that site effects have had a disproportionately high impact on structures, for example 22nd February 2011, **M**6.3 Christchurch, New Zealand earthquake (Bradley and Cubrinovski 2011). One of the most common of these effects is site amplification. This occurs when near surface deposits increase shaking felt at the surface compared to the expected bedrock shaking (Kramer 1996). This



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 1 **a** The USGS Shake Intensity Map of **M**7.8 Gorkha, Nepal earthquake (USGS 2015b), the *black rectangle* marking the rupture plane and epicentre. (**b**) Areas investigated for site effects in the Kathmandu Valley (EEFIT 2016; Google Maps 2016)

is often caused by less stiff deposits in the near surface. With recent improvements in testing equipment, it is possible to determine preliminary values of soil properties, enabling the assessment of site amplification. Though invasive methods can be used to determine the final soil parameters, the non-invasive, passive, geophysical tests used in this study are inexpensive and easily portable making them ideal for rapid, post-earthquake deployment. The results of such a survey can then be used to refine and guide future invasive investigations. One of the aims of the EEFIT Nepal mission was to determine preliminary quantitative values of shear wave velocity (V_s) for the severely damaged areas of Kathmandu and for the main seismic station, USGS KATNP, in the region.

2 Geological setting

The Kathmandu Valley is over 20 km wide, containing the capital city as well as several satellite cities such as Bhaktapur (Fig. 1). The fill sediments in the valley consist of a recent, uncemented, heterogeneous mixture of clays, sands and silts reaching a thickness of over 400 m, deposited in a Pleistocene lake (Aydan and Ulusay 2015). This is comparable to the lacustrine sediments of the Mexico City Basin, where a **M**8.5 earthquake in 1985 caused widespread destruction across Mexico City as a result of site amplification and building resonance, despite epicentral distances of over 350 km (Campillo et al. 1989). The similar geology highlights the potential for significant localised site amplification. Previous studies, including Piya (2004) which investigated liquefaction potential in the region, have shown the potential for basin effects and site amplification.

The Kathmandu Valley is located in the central part of the active Himalayan orogenic belt, formed by the collision of the Indian Plate and the overlying Eurasian Plate (Avouac et al. 2015). The plate boundary accommodates around 20 mm/year of convergence (Searle et al. 2008) and a number of notable earthquakes have occurred along it (Bilham et al. 2001) including the 1934 **M**8.0 Bihar earthquake, which killed 19,000 people in Nepal (Ader et al. 2012). The April 2015 earthquake occurred in a previously identified seismic gap (Bilham et al. 2001). The fault ruptured eastward from the initiation point North-West of Kathmandu for approximately 140 km (Avouac et al. 2015). The location and focal mechanism indicated that the source of the earthquake was the Main Himalayan Thrust (Avouac et al. 2015).

Earthquake damage was examined by the mission throughout the Kathmandu Valley, particularly in the historical parts of the city which suffered major structural failures. From observations in central Kathmandu, it was noticeable that the majority of newer structures remained standing, with relatively few buildings suffering significant damage. This was in part because of the nature of the earthquake, with the maximum amplification occurring at a period higher than the fundamental period of the majority of buildings (USGS 2015a); the majority of building stock seen were less than five stories with a fundamental period of 0.5 s or less and the largest earthquake amplification occurred around 5 s. There were also smaller pockets of more severe damage observed to buildings of all sizes, particularly in the historical parts of the city and suburbs and in some areas along the Bishnumati River. Earlier investigations have suggested that these were the result of site amplification (e.g. Goda et al. 2015).

3 Method of investigation

In order to understand the role of site conditions on Nepal's building damage, four locations were chosen for investigation (Fig. 1b): Bungmati (27.62930389°N, 85.30364019°E) and Bhaktapur (27.67172202°N, 85.42809284°E) in regions which both contained concentrations of historic unreinforced masonry buildings with severe damage; Balaju Park in the Siddhitol Region (27.733902°N, 85.301356°E) along the Bishnumati River, near where a concentration of foundation failures, soft storey failures, and tilting buildings were observed; and the Annapurna Hotel (27.711100°N, 85.315698°E), chosen partly as it was in an area of low damage. The latter also provided a location with relatively undisturbed land close to the KATNP seismic station, the main earthquake recording station in the Kathmandu valley.

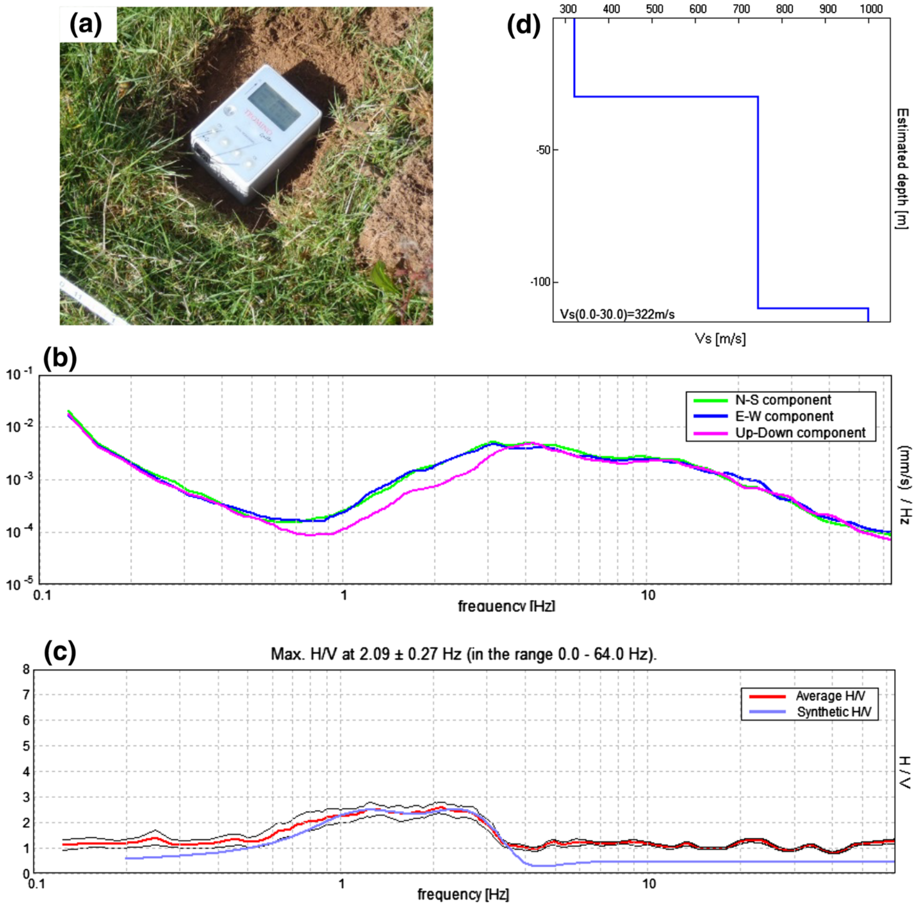


Fig. 2 Method of Microtremor testing using **a** Tromino Zero (Micromed 2013b) with Grilla Software (Micromed 2013a). The recordings are converted to the frequency domain using a Fast Fourier Transform (**b**). The horizontal components are then geometrically averaged and normalised by the vertical to produce the H/V plot (**c**). This is synthetically modelled using the V_s profile (**d**)

Microtremor, Horizontal/Vertical Spectral Ratio (HVSR) testing was carried out in each of the locations. This is a non-invasive, geophysical method which uses ambient noise. During the mission, a single station, passive technique was used (Fig. 2). This can determine an upper bound for the fundamental frequency of a site, important for structural engineering, but it also provides an indication of the V_s profile at a site. This is useful for calculating ground response transfer functions and for developing ground motion prediction equations. This method was chosen for its ease of deployment and its low cost compared to invasive measurements. The digital seismometer used is small, portable and its measurements are of short duration (recordings of 14 min were used for a depth of 30 m). It can be deployed as a single measurement, for example, by a damaged building or as a series of measurements which can be processed as a traverse revealing the pseudo-seismic stratigraphy (Fig. 3).

A highly sensitive, digital, combined seismometer and accelerometer was used to measure surface waves within the ground from 0 to 64 Hz; in this case a Tromino donated to the mission by Moho and University of Bologna (Micromed 2013b) (Fig. 2a). The surface waves are assumed to be predominantly elliptical Rayleigh waves which are frequency dependant in a non-homogenous layered medium (Kramer 1996). The depth dependence of the Rayleigh wave motion is reliant on the subsurface velocity structure such that there is a change in ellipticity at geological boundaries. This change is determined from the three components of the instrument: two perpendicular horizontal components and one vertical component. The recording is converted to the frequency domain with a Fast Fourier Transform, showing the three components (Fig. 2b) smoothed by 10 % through triangular windowing of 20 s. Windows were removed to “clean” transient noise within the trace, ensuring a minimum of 70 % of the trace remained, but more generally 80–90 % was kept. Using the H/V method of Nakamura (1989), the two horizontal

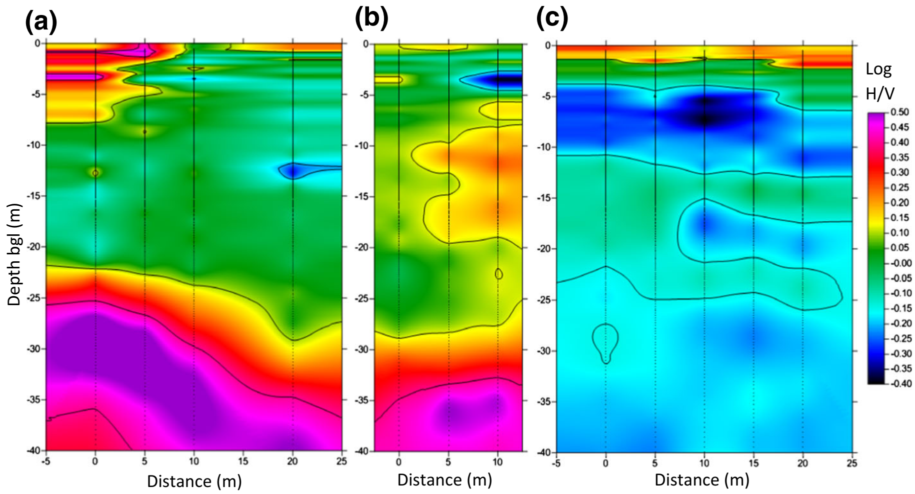


Fig. 3 Cross-sections of traverses carried out at **a** Balaju Park, Siddhitol, **b** Bishnumati River Bank, Siddhitol and **c** Annapurna Hotel, Central Kathmandu (Fig. 1). The *black/dark grey* colouring represents a stiff material such as rock while the *white* is a less stiff indicating more soil-like material. The results indicate a rock-like material in the Balaju Park and Siddhitol Region at around 20–30 m bgl with soil above. There is some thin hard layering in from −5 to 0 m distance in (**a**). This is thought to be caused by an open drain seen adjacent to the recording. In contrast at the Annapurna Hotel results (**c**) indicate a thicker soil layer. The thin stiff layer at the surface is believed to be a manmade layer

component spectra are geometrically averaged and divided by the vertical component forming an H/V plot (Fig. 2c).

If a sufficient difference in the strata stiffness is present, peaks are formed in the H/V plot at the boundary layers due to the change in ellipticity of the waves (Bard 1999). The largest peak is considered to be formed close to the fundamental frequency of the site. If the depth of the first layer can then be constrained, the remaining shear wave (V_s) velocities can be calculated iteratively as follows:

$$f_0 = V_s/(4T) \tag{1}$$

where f_0 is frequency, V_s is shear velocity and T is the thickness of each individual layer (Kramer 1996). The frequencies are known in the H/V plot (Fig. 2d). These are modelled to the main peaks in the H/V trace as the synthetic model (Fig. 2c) (Castellaro and Mulargia 2009).

The method has some limitations. It is indeterminate, requiring one parameter of the soil profile to be known before analysis can be carried out (Castellaro and Mulargia 2009), commonly the thickness of the first stratum. However, as so few accessible borehole records exist in Kathmandu, the recordings were constrained instead by previous microtremor V_s measurements carried out by Paudyal et al. (2012) and the Wald and Allen (2007) topographical proxy method implemented in the Kathmandu Valley by Goda et al. (2015). These values were used as the initial V_s velocity of the first layer revealing its thickness from the first peak (Eq. 1). The amplitude of the first peak is empirically proportional to the impedance ratio, Eq. 2 (Kramer 1996), between the first and second layer (Castellaro and Mulargia 2009). Thus, the V_s velocity of the second layer can be determined and so on until a complete V_s profile is determined through iteration.

$$\alpha_z = \frac{V_{s_2}\rho_2}{V_{s_1}\rho_1} \tag{2}$$

where α_z is the impedance ratio, V_{s_1} is the V_s velocity of the first layer, ρ_1 is density of the first layer, V_{s_2} is V_s velocity of the second layer and ρ_2 is density of the first layer.

Several estimates were formed for each site, each of which forming a possible solution. These were compared to both the geological profiles of the area developed by Paudyal et al. (2012) and other solutions in terms of stability before the final estimate was chosen. This processing is similar to Cox et al. (2015) method of determining the site signature from geophysical dispersion curves, though more simply implemented. When more invasive testing has been carried out, the recordings can be more fully processed. In their current state, they should be used with caution and should only be considered as preliminary estimates of ground characteristics.

The HVSR method also depends on surface waves already present in the ground. These can be masked or be influenced by human and environmental noise, such as the evident reconstruction works in Nepal or velocity reversals in the near surface, a feature common in made ground. Both these effects removed evidence of any true stratigraphic changes in the near surface by causing dominating peaks or troughs in the trace, overshadowing any that would be caused by changes in the deposits (Fig. 4b).

Undisturbed traverses of ground were hard to find in the damaged areas of the Kathmandu Valley. For this reason, in Bungmati and Bhaktapur only single measurements were carried out, rather than the preferred several recordings. Natural variation within the ground means that single measurements are more open to interpretation. In the traverses several recordings are compared to determine if the H/V traces are consistent, making it

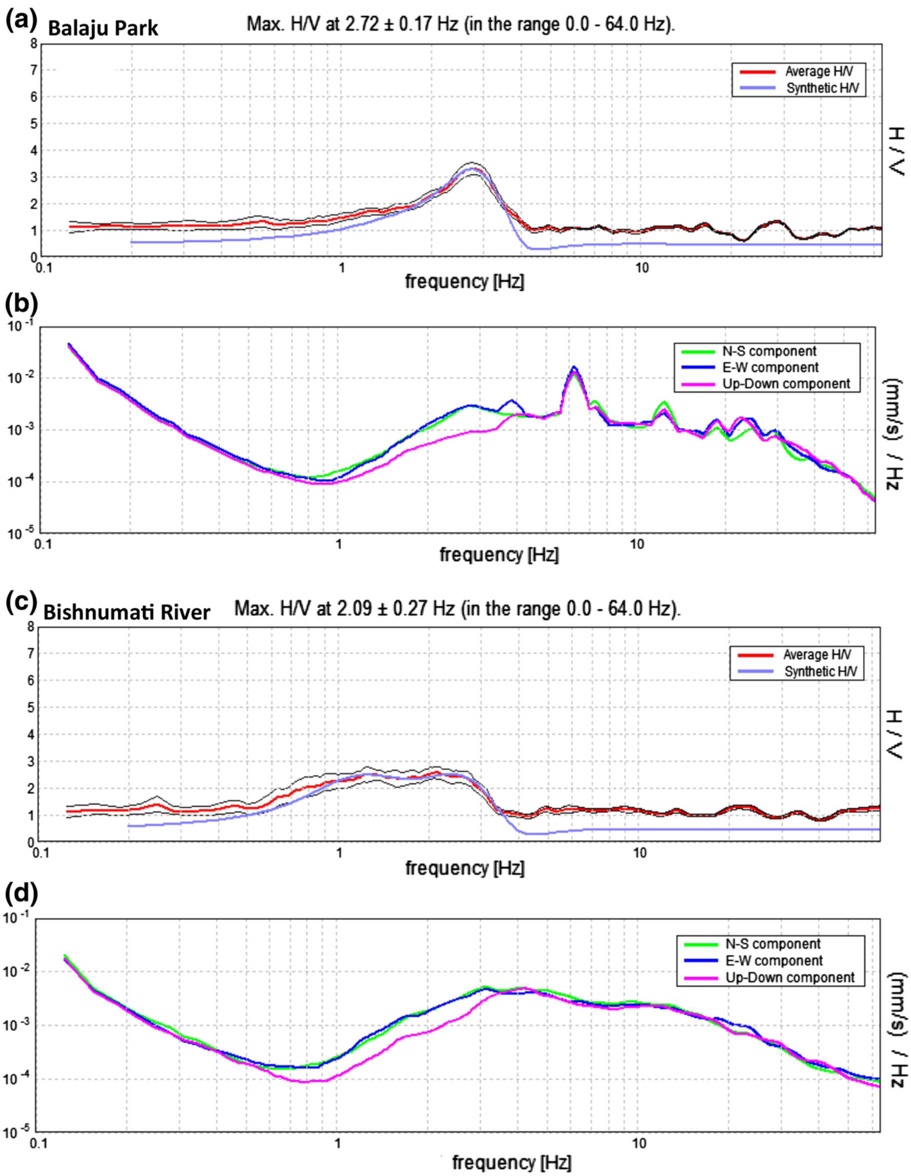


Fig. 4 **a** and **c** are H/V traces with (**b**) and **d** being the relevant Fourier component spectra, processed as in Fig. 2. **a** and **b** are recorded from Balaju Park, Siddhitol and noise interference in the trace is clearly visible as spikes in all components for frequencies over 4 Hz in chart (**b**) (SESAME 2004). This spiking is absent in Bishnumati River bank recording (**c**) and (**d**). However, both (**b**) and (**d**) have clear 'eye' shapes where the vertical comes away from the horizontal components between 1 and 4 Hz indicating stratigraphic peaks (SESAME 2004)

easier to determine interference in the trace. In addition, single measurements were more likely to be disturbed by anthropogenic noise during recording as they were taken near to people's homes.

Table 1 Preliminary results from microtremor measurements (EEFIT 2016)

	Indicated depth to bedrock	H/V fundamental frequency*	V_{s30} from modelling H/V traces (m/s)	Eurocode site class (CEN 2004)	Main uncertainty associated with result
Hotel Annapurna near American Embassy (for Station KATNP)	>150 m	0.31 Hz ± 0.13	305	C	Inversion in near surface may obscure effects on V_{s30} of near-surface soil column
Balaju Park, Siddhitol	~27 m	2.65 Hz ±0.26	304	E	Layer at 27 m considered to be bedrock but would need to be confirmed through invasive testing
Bhaktapur	>250 m	0.43 Hz ± 0.07	205	C	Only single recordings, no traverse

* It should be noted that H/V fundamental frequency is an upper limit of the shear wave fundamental frequency

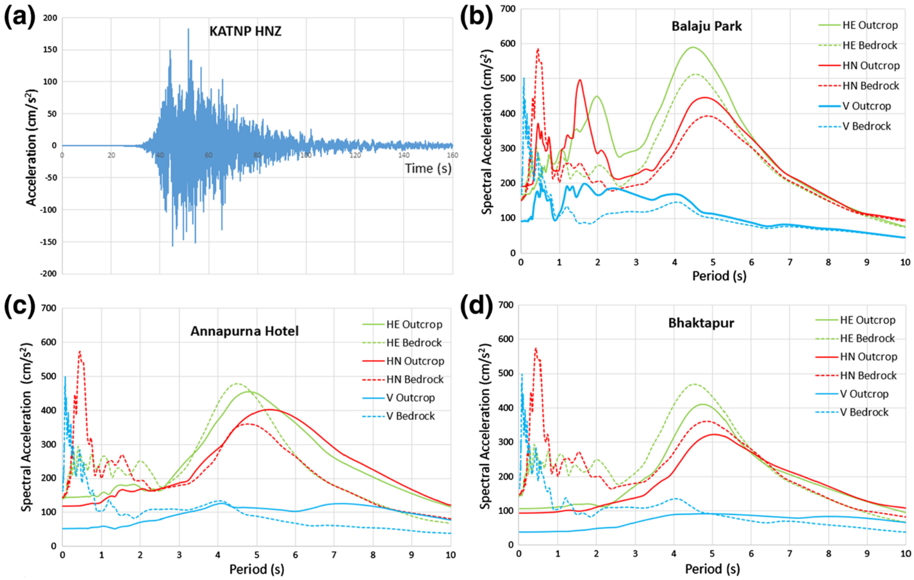
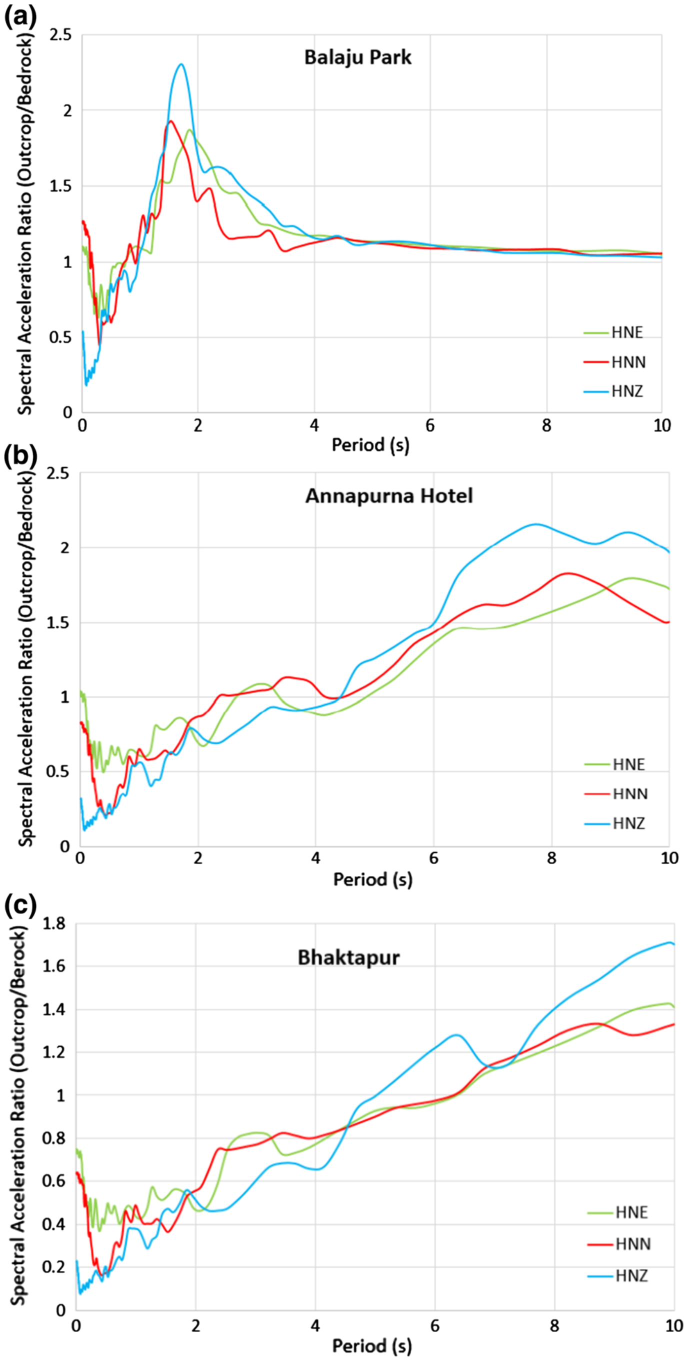


Fig. 5 **a** Acceleration input motion (USGS 2015a) used to create spectral acceleration plots for each of the different areas tested, which are shown in (**b**, **c**, **d**). All sites are modelled as soil profiles in DEEPSOIL (Hashash et al. 2015a) using the mean limit of Seed and Idriss (1970) shear modulus degradation and damping curves with strain. The complex shear modulus is modelled as frequency independent. Each profile had 100 iterations. All three accelerometer components are modelled with 'HE outcrop' representing the horizontal eastern direction of the outcrop response, 'HN outcrop' representing the horizontal northern direction of the outcrop response and 'V outcrop' representing the vertical component of the outcrop response. The bedrock response is similarly modelled in the three components and is plotted with the dotted lines. The large response around 5 s comes from energy content in the initial recording, but the response still varies dramatically between the sites, particularly at shorter periods



Despite these limitations, the test method is valid as the site specific spectra obtained indicate the general influence of the soil conditions on building performance. It is important for this to be carried out as soon as possible after the earthquake, as worst

◀**Fig. 6** Spectral acceleration ratios of the outcrop acceleration/bedrock acceleration calculated from Fig. 5b–d. The ratios at both the Annapurna Hotel (**b**) and Bhaktapur (**c**) appear similar with significant de-amplification in the lower periods. Amplification occurs above 5 Hz in Bhaktapur (**c**) and around 4 Hz in the Annapurna Hotel (**b**) which has larger amplifications of over 2. Balaju Park (**a**) is dissimilar showing some de-amplification, but this swiftly becomes a peak of amplification at an average of 1.5 Hz

affected areas are often the focus of initial rebuilding efforts. Thus, the measurements can be used to clarify if site effects occurred and indicate whether further testing, additional design or ground improvement is required for the rebuild.

The field measurements were acquired using a Tromino instrument (Micromed 2013b) according to the best practice outlined in the SESAME guidelines (2004). All measurements were acquired in confined urban areas. The traverse profiles were created from single station measurements carried out every 5 m. The field data from testing were processed using Moho Grilla Software (Micromed 2013a).

4 Results

Cross-sections of the pseudo-seismic stratigraphy are formed using a series of H/V traces. Assuming a common V_s for the traces, the H/V records are converted from frequency to thickness along the vertical axis (Eq. 1) with the log of the H/V amplitude forming the contours (Fig. 3). The traces are then correlated horizontally using the spatial correlation technique kriging (Wald et al. 2011), developing an indication of the near surface ground conditions (Fig. 3). The V_s assumed for each plot was the V_{s30} determined from the H/V traces for the recording site. The microtremor recordings were carried out 5 m apart and are indicated by the black dotted lines (Fig. 3). One measurement at 15 m for the Balaju Park (Fig. 3a) was not used as it has high noise interference which obscured the stratigraphic trace.

Profiles from the Siddhitol Region, at the valley edge, show bedrock at around 20–25 m from below ground level (bgl) in Balaju Park (Fig. 3a) deepening to 25–30 m bgl near the Bishnumati River Bank (Fig. 3b), establishing the bedrock trend at the edge of the valley. The profiles from the Annapurna Hotel (Fig. 3c), situated more centrally in the basin, indicate deep sedimentary deposits extending to well over 40 m bgl. A bedrock layer is detected several tens of metres bgl, however, the measurement points are spaced too widely to resolve the level accurately. Due to the difference in bedrock depth at these sites, there may be a completely different ground response depending on whether the rock or soil was more affected by the earthquake frequencies despite similar V_{s30} values determined by synthetically fitting the H/V curve (Table 1).

The Annapurna Hotel cross-section (Fig. 3c) highlights the problem of velocity reversals in made ground. The top layer has a thin stiff layer at the ground surface which causes an equally, strong negative contrast underneath, forming a dipole from −5 to −10 m. This dipole does not reflect the nature of the deposits and so the layers in this region become masked (SESAME 2004). Thus, the near-surface strata that could have an effect on the V_s profile are concealed. The exact nature of these materials can only be obtained from invasive investigations. However, as the bedrock peak frequency and general H/V traces were highly consistent within the traverse and matched that of previous investigations (Paudyal et al. 2012), these results were still considered to be valid in this preliminary assessment and were included with their main uncertainty outlined (Table 1).

The human and environmental noise is visible in the H/V traces for the Siddhitol Region after processing (Fig. 4). Narrow peaks can be seen in the higher spectral frequencies at the Balaju Park site (Fig. 4b). These are caused by man-made surface waves, possibly by the building works nearby. These affect the H/V trace for the site (Fig. 4a) which has small "peaks" which are not in fact stratigraphic.

These peaks are absent from the spectral trace near Bishnumati River (Fig. 4d), close to Balaju Park, a relatively quiet part of the city. The river site is in undisturbed soil rather than made ground. This gives a classic H/V peak of a low impedance contrast rock (Fig. 4c) which is elongated rather than the sharp peak found in the Balaju Park (Fig. 4a) which may have been disrupted by the interference. In addition, the subtle peaks representing near subsurface strata may not be visible in the Balaju Park profile because they are masked by the noise peaks. However in general, both sites correlated well in V_{s30} and H/V fundamental frequency summarised in Table 1 along with the main areas of uncertainty.

In Bhaktapur, individual measurements were carried out in the damaged old section of the town and in Bungmati near to collapsed buildings. In both of these towns, no clear centre of undisturbed earth was found close enough to the damaged buildings for a good comparison, therefore transects were not attempted. The recordings that were taken were sited on made ground, therefore there were disturbances in the trace particularly in the vertical spectral component. In Bungmati, the traces were too disturbed by environmental noise to be used and the results are therefore not included in Table 1. This was suspected to be due to poor ground contact with the accelerometer in the north component. However, when compared to the east horizontal component alone, the trace was similar to that of Bhaktapur with deep bedrock of over 250 m. Some intermediate layers were seen in the Bungmati trace, but both sites had similar fundamental frequencies (Table 1).

5 Spectral acceleration

In order to understand the influence of the site amplification that had occurred, the V_s profiles are modelled and analysed using DEEPSOIL (Hashash et al. 2015a). Two points within the modelled profiles were compared: at the interface between bedrock and soil (the 'bedrock' response) and at the ground surface (the 'outcrop' response). The sites are modelled as nonlinear using equivalent linear processing in the frequency domain, using discrete points. The main uncertainty is the lack of availability of soil properties in Nepal (Hashash et al. 2015b). Despite efforts of NSET and other organisations, direct geotechnical measurements are not available. Therefore, the Seed and Idriss (1970) model was used for the shear modulus degradation and damping curves with strain. This model is chosen as the stiffness indicated by the microtremor results is consistent with a predominantly sandy soil and required fewer parameters than other models.

The input motion used for the analysis was the recording from the KATNP station (USGS 2015a). This is the only strong motion recording of the earthquake currently freely available (Fig. 5a). KATNP is not located on bedrock, therefore, interference is visible from the outcrop response to the strong low frequency shaking. This causes a much larger bedrock response at around 5 s than would ever be expected at all three sites (Fig. 5b–d).

However, the ratios of the bedrock and outcrop responses from this basic calculation are significant (Fig. 6). In Balaju Park (Fig. 5a), there is a strong response of up to 586 cm/s^2 from the bedrock in the lower periods. This is similar to the bedrock response at both Bhaktapur (Fig. 5d) and the Annapurna Hotel site (Fig. 5c). However, at Bhaktapur and the Annapurna Hotel, the outcrop response remains low in the shorter periods. The ratio of outcrop acceleration/bedrock acceleration for both sites (Fig. 6b, c) indicates that the soil column above the bedrock damps the response, being significantly less than one. Due to the thinner soil layer, in Balaju Park large amplifications of over twice the original input motion could occur at the surface as indicated by the ratio of outcrop/bedrock acceleration (Fig. 6a) and are possibly the reason for the devastation in the region.

These results provide quantitative indication that region of Siddhitol near Balaju Park did undergo site effects. Balaju Park appears to have been affected by the shallow bedrock, having a much higher amplitude response in shorter periods, closer to the natural frequency of the structures in this region. The location at the edge of the Kathmandu Valley may have contributed to this due to basin effects. However, the nature of damage observed during the mission indicates that while these buildings may have been more heavily excited. Collapses were also likely influenced by bearing capacity failures due to inadequate foundations or site preparation.

It is also notable in Bhaktapur that the ratio of amplification (Fig. 6c) is generally lower than that at the Annapurna Hotel (Fig. 6b), not being more than 1.8 times more than the input motion. This does not reflect the level of damaged observed on the mission at each of the sites: little/repairable damage at the Annapurna Hotel and unrepairable/catastrophic damage in Bhaktapur. Therefore, the damage in Bhaktapur is expected to have been caused by structural failures, with the generally older buildings in the town performing poorly under the earthquake loading compared to the newer buildings in the region of the hotel.

6 Comparison to the Nepalese Building Codes

To evaluate the adequacy of the current Nepalese Building Codes (NBC 1994), the results from Balaju Park are compared to the recommended coefficients from the code. This is based on a response spectrum graph. However, the code is fairly unusual as considerations for the building design, location and importance factors are all included within the primary spectra. Thus, the spectrum was created for a reinforced masonry building of high importance, for example a hospital, within the Kathmandu Valley (NBC 1994).

Though the amplification from the input station is already included in the results and so the amplification is higher than expected particularly in the longer periods, Fig. 7, it is clear that the current building code will need to be revisited. While accelerations at the short period end of the spectrum are within code limits, once above approximately one second, accelerations experienced at Balaju Park clearly exceed the code parameters. The code should have accounted for the short period amplification around 0.5 s (2 Hz). The code for soft soil does capture most of this motion, but the Siddhitol Region would be more likely to be considered as a medium soil or rock site due to the depth of the bedrock. In addition, these results should be refined by further in situ investigation of this region such that accurate shear moduli may be determined and used.

However, this exceedance has significance for regions of similar geology outside Nepal. Siddhitol is on the edge of a deep valley basin which is not an uncommon environment in surrounding countries. Other national codes should be checked in light of these results, particularly to ensure that site amplification is sufficiently taken into account.

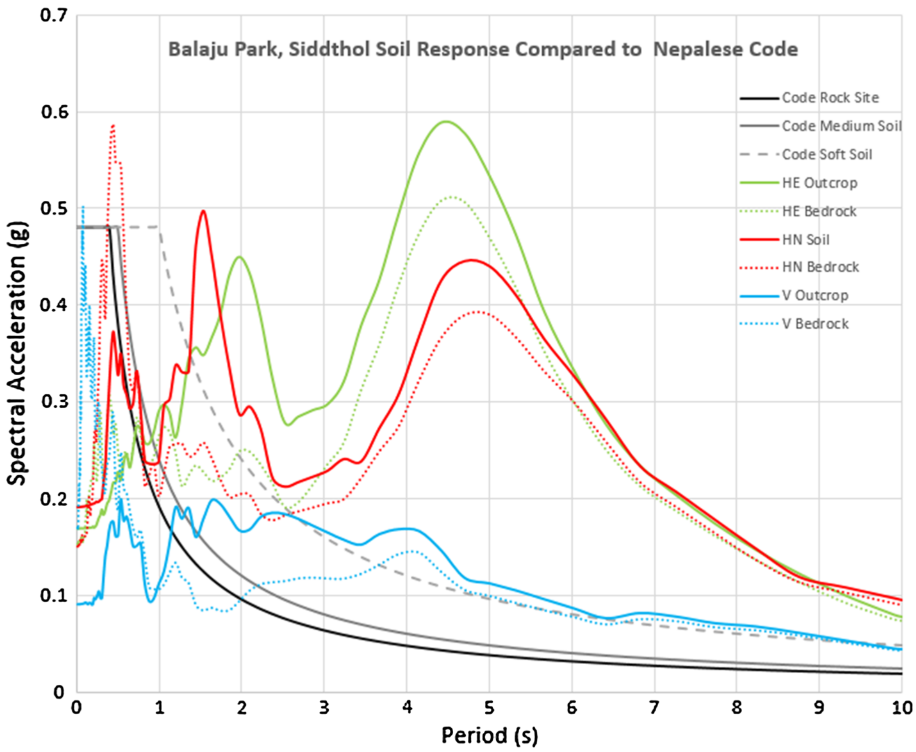


Fig. 7 Comparison of the Nepalese Building Code (NBC 1994) design spectra with the acceleration spectra of Balaju Park, Siddhitol (Fig. 5b). Though the true response is not thought to be as high an acceleration as modelled by the bias input motion around 5 s, Fig. 5a, it is noticeable that at all periods above 1.5 s the code appears not to be sufficient for any soil type

7 Conclusions

Passive microtremor measurements, obtained from several sites in the Kathmandu Valley following the **M**7.6 Gorkha earthquake, have been used to estimate V_s velocity profiles for significantly damaged areas as well as near the KATNP station. These results indicate areas of likely site amplification, such as the Siddhitol Region near the edge of the Kathmandu Valley. This is likely to have undergone site amplification of the initial rock strong motion with possible basin effects. The resulting ground motions exceed the design levels for certain period ranges from the Nepalese Building Codes (NBC 1994), indicating the need for site-specific hazard analysis and for revision of the building code to address the effect of site amplification.

While this analysis helps to explain the pattern of damage observed in the Kathmandu Valley, these results can only be considered as general indications of what has occurred during the earthquake. Without site-specific soil testing to provide geotechnical parameters and invasive testing for correlation of the microtremor measurements, the results are not sufficiently accurate to use for specific design or for detailed upgrading of the current building code. However, the geology in this region is not unique and both building codes and building practices should be reviewed. Particularly as limited building damage to engineered structures in many areas of Kathmandu may have occurred because the structures were not significantly excited by the unique long period ground motions and, thus, were not tested as they may be in the future.

It has been acknowledged by others that the timing and nature of this earthquake meant the widespread devastation was not the worst case scenario expected (e.g. Avouac et al. 2015). More work is needed to ensure the security of such vulnerable communities to prevent future devastation. A good first step will be the publishing of the other recordings of the Gorkha Earthquake, including those taken on bedrock.

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Authors contribution This study was conceived by S.T.W & B.G. The fieldwork was carried out in two teams, the first S.T.W., P.B. & M.W. carried out the studies in Siddhitol and at the Annapurna Hotel. The second S.T.W., S.D., G.F. & A.T. in Bhaktapur and Bungmati. All authors contributed in the initial stages of the paper with observations and ideas. S.T.W. processed and analysed the data which was reviewed by B.G. The paper was written by S.T.W. which was academically supervised by S.W. and C.F. The paper was then reviewed and discussed by all authors.

Data supporting this publication is openly available under an 'Open Data Commons Open Database License'. Additional metadata are available at: http://dx.doi.org/10.17634/101595-1. Please contact Newcastle Research Data Service at rdm@ncl.ac.uk for access instructions.

References

Ader T, Avouac JP, Liu-Zeng J, Lyon-Caen H, Bollinger L, Galetzka J, Genrich J, Thomas M, Chanard K, Sapkota SN, Rajaure S, Shrestha P, Ding L, Flouzat M (2012) Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: implications for seismic hazard. J Geophys Res 117:B04403

Avouac JP, Meng L, Wei S, Wang T, Ampuero JP (2015) Lower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquake. Nat Geosci 8:708–711

Aydan O, Ulusay R (2015) A quick report on the 2015 Gorkha (Nepal) earthquake and its geo-engineering aspects. IAEG. www.iaeg.info. Accessed 26 Sept 15

Bard P (1999) Microtremor measurements: a tool for site effect estimation? In: Irikura K, Okada S-T (eds) The effects of surface geology on seismic motion. Balkema, Rotterdam

Bilham R, Gaur VK, Molnar P (2001) Himalayan seismic hazard. Science (Washington) 293(5534):1442–1444

Bradley BA, Cubrinovski M (2011) Near-source strong ground motions observed in the 22 February 2011 Christchurch earthquake. Seismol Res Lett 82(6):853–865

Campillo M, Gabriel JC, Aki K, Sanchez-Sesma FJ (1989) Destructive strong ground motion in Mexico City: source, path, and site effects during great 1985 Michoacan earthquake. Bull Seismol Soc Am 79(6):1718–1735

Castellaro S, Mulargia F (2009) V_{s30} estimates using constrained H/V measurements. Bull Seismol Soc Am 99(2A):761–773

Cox BR, Griffiths SC, Rathje EM, Teague DP (2015) Shear wave velocity uncertainty and its relation to variability in site response using a dispersion misfit approach. In: 6th International conference on earthquake geotechnical engineering. 1–4 November 2015, Christchurch

EEFIT (2015) The earthquake field investigation team. www.istructe.org. Accessed 20 Oct 2015

EEFIT (2016) The Gorkha earthquake of 25th April 2015. EEFIT field report. ISTRUCTE, London

Goda K, Kiyota T, Pokhrei RM, Chiaro G, Katagiri T, Sharma K, Wilkinson S (2015) The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. Front Bull Environ 1:8

Google Maps (2016) Google maps. Google, New York. www.google.co.uk/maps/. Accessed 08 Jul 2016

Hashash YMA, Musgrove MI, Harmon JA, Groholski DR, Phillips CA, Park D (2015a) DEEPSOIL 6.1, User manual. Board of Trustees of University of Illinois at Urbana-Champaign, Urbana

Hashash YMA, Tiwari B, Moss RES, Asimaki D, Clahan K, Kieffer DS, Dreger DS, Macdonald A, Madugo CM, Mason HB, Pehlivan M, Rayamajhi D, Acharya I, Adhikari B (2015b) Geotechnical field reconnaissance: Gorkha (Nepal) earthquake of April 25 2015 and related shaking sequence. Geotechnical extreme event reconnaissance. GEER Association report no. GEER-040 Version 1.1

Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall, New York

MICROMED (2013a) Grilla ver. 6.4, spectral and HVSR analysis. Micromed, Treviso

MICROMED (2013b) Tromino. www.tromino.eu. Accessed 16 Oct 2014

Nakamura Y (1989) Method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Q Rep of RTRI (Jpn) 30(1):25–33

NBC (1994) NBC 105: 1994. Nepal National Building Code: seismic design of buildings in Nepal. Kathmandu, Nepal. Government of Nepal, Department of Urban Development and Building Construction

NSET (2015) Earthquake 2015. www.nset.org.np. Accessed 20 Oct 15

Paudyal YR, Yatabe R, Bhandary NP, Dahal RK (2012) A study of local amplification effect of soil layers on ground motion in the Kathmandu Valley using microtremor analysis. Earthq Eng Eng Vibr 11(2):257–268

Piya BK (2004) Generation of a geological database for the liquefaction hazard assessment in the Kathmandu Valley. MSc dissertation, International Institute for Geo-Information and Earth Observation, Netherlands

Searle MP, Law RD, Godin L, Larson KP, Streule MJ, Cottle JM, Jessup MJ (2008) Defining the Himalayan Main Central Thrust in Nepal. J Geol Soc 165:523–534

Seed HB, Idriss IM (1970) Soil moduli and damping factors for dynamic response analyses. Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, California, 40

SESAME (2004) Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation. SESAME European Research Project WP12, deliverable D23.12. http://sesame-fp5.obs.ujf-grenoble.fr/. Accessed 16 Oct 14

USGS (2015a) 25th April 2015 Gorkha earthquake. Available from: http://earthquake.usgs.gov/earthquakes. Accessed 20 Oct 2015

USGS (2015b) Shake intensity map for 25th April 2015 Gorkha earthquake. http://earthquake.usgs.gov/earthquakes/eventpage/us20002926#impact_shakemaps. Accessed 11 Mar 2016

Wald DJ, Allen TI (2007) Topographical slope as a proxy for seismic site conditions and amplification. Bull Seismol Soc Am 97(5):1379–1395

Wald DJ, McWhirter L, Thompson E, Hering AS (2011) A new strategy for developing V_{s30} maps. In: 4th IASPEI/IAEE international symposium: effects of surface geology on seismic motion. August 23–26, 2011. University of California Santa Barbara