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An investigation of effect of 2015 Gorkha Earthquake within the World Heritage monument zones of Kathmandu Valley

Une enquête sur l'effet du tremblement de terre de Gorkha de 2015 dans les zones de monuments du patrimoine mondial de la vallée de Katmandou

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ABSTRACT: On April 25, 2015, Kathmandu Valley was dramatically altered by the Gorkha Earthquake (M_w=7.8) causing huge damage to the UNESCO world heritage monuments. This study focuses on identifying the causes of collapse or damage in the ancient structures by investigating the geotechnical characteristics of the soil supporting them and also by collecting the associated damage evidence of the monuments. Geotechnical site investigation and structural damage pattern assessment were conducted at five heritage sites in Kathmandu during 2017-2018. The results of investigations revealed the presence of soft soil strata within the Hanuman Dhoka Durbar square which corroborated with the extensive damage recorded highlighting the importance of local site effect. The detailed laboratory testing results as shown for Jaisidewal temple site is required to study effect of dynamic soil-structure interaction on the heritage structure performance. Damaged evidence of structure pointed out that the age-related deterioration of the construction materials, loosening of the bonding of the masonry units, and poor connection within the composite structures were the main reason of collapse. The periodic inspection and maintenance of existing monuments would increase the seismic resilience of these structures.

RÉSUMÉ : Le 25 avril 2015, la vallée de Katmandou a été considérablement modifiée par le tremblement de terre de Gorkha (Mw=7,8) causant d'énormes dommages aux monuments du patrimoine mondial de l'UNESCO. Cette étude se concentre sur l'identification des causes d'effondrement ou de dommages dans les structures anciennes en étudiant les caractéristiques géotechniques du sol qui les supporte et également en recueillant les preuves de dommages associés des monuments. Une étude géotechnique du site et une évaluation des dommages structurels ont été menées sur cinq sites patrimoniaux à Katmandou en 2017-2018. Les résultats des investigations ont révélé la présence de strates de sol meuble au sein de la place Hanuman Dhoka Durbar, ce qui corrobore les dommages importants enregistrés, soulignant l'importance de l'effet de site local. Les résultats détaillés des tests en laboratoire, tels qu'ils sont indiqués pour le site de Jaisidewal, sont nécessaires pour étudier l'effet de l'interaction dynamique sol-structure sur la performance de la structure patrimoniale. Des preuves endommagées de la structure ont souligné que la détérioration des matériaux de construction liée à l'âge, le relâchement de la liaison des éléments de maçonnerie et une mauvaise connexion au sein des structures composites étaient la principale raison de l'effondrement. L'inspection et l'entretien périodiques des monuments existants augmenteraient la résilience sismique de ces structures.

KEYWORDS: brick masonry; geotechnical investigation; reconnaissance survey, field and laboratory testing.

1 INTRODUCTION

Kathmandu Valley of Nepal is surrounded by the Himalayan mountain range on all the sides and having the deposition of soft lake sediments of Plio-Pleistocene origin where the thickness of sediments is more than 650 m in the central portion of the valley (Dhital, 2015). The valley has three districts viz. Kathmandu, Lalitpur and Bhaktapur. Several damaging earthquakes have been reported in Nepal and surrounding areas since thirteen centuries including 1934 Great Nepal-Bihar earthquake (M_w= 8.1), 1988 Udaypur earthquake (M_w= 6.9), 2011 Sikkim-Nepal earthquake due to subduction of two major tectonics plate boundaries, Indian plate subducting beneath the Eurasian plate (Dixit et al. 2015). The Gorkha earthquake of April 25th, 2015 and the aftershocks are latest in the list of devastating earthquakes in Nepal and neighboring areas of India. The earthquake of M_w 7.8 with its epicenter near Baluwa village (77 km northwest of Kathmandu) dramatically altered the valley and whole of Nepal (Figure 1). It triggered massive landslides, rock fall, and avalanches and caused severe destruction to the capital city, Kathmandu. The mainshock (M_w=7.8) and major aftershocks (M_w=6.6 and 6.7 and 7.3) killed around 9000 people, displaced 2.8 million populations, destroyed 500,000 homes and undermined the sustainability of Nepal's tourist industry.

The earthquake also brought cultural disaster within the Kathmandu Valley damaging 403 monuments (Gautam 2017, Gautam et al. 2017). The valley is home to seven UNESCO world heritage monument zones where Hanuman Dhoka Durbar Square, Swayambhu, Budhanath and Pashupatinath are located within Kathmandu district; Bhaktapur Durbar Square and Changu Narayan within Bhaktapur district and Patan Durbar Square within Lalitpur district. These ancient structures are major source of attraction and account for 7.6% of GDP across Nepal indicating the importance of cultural structures in urban Nepal. These sites are not only important for economy but also the focal point of intangible values and the tradition of Nepal (Davis et al. 2020). Weise et al. (2017) stated that this earthquake damaged many vernacular buildings and historical monuments, including 190 collapsed and 663 partially damaged. Coningham et al. (2016&2019) reported the death of over 70 people by collapse of one of the Kathmandu's oldest monument, the Kasthamandap located within Hanuman Dhoka Durbar Square constructed around 12th century. However, not all types of ancient structures collapsed or suffered extensive damage. A study carried out by Kc et al. (2019) reported that the heritage structures made of dome performed very well compared to Nepalese Pagoda style temples and Shikhara style temples. The extensive damage reported on the heritage structures of Nepal drove several researchers to understand the structures that survived this seismic sequence and document the damaged structures. Rapid visual damage assessment, digitization of the monument data and non-intrusive techniques were employed by several researchers to understand the structural conditions of the damaged and survived structures (Didier et al. 2017).

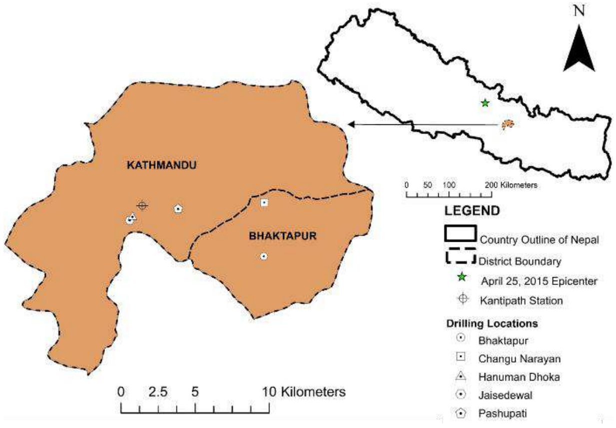

Figure 1. Location of ground investigation carried out in Kathmandu and Bhaktapur district of Kathmandu Valley within the World heritage monument zones and the location of the main shock event of 25th April, 2015.

While a considerable amount of research has already been done to understand the seismic safety of heritage structures within Kathmandu Valley (Shakya et al. 2014, Bhagat et al. 2018, Dais et al. 2021), a little work has been done that can integrate the impact of local ground condition on the damages observed within the monument zones of the Kathmandu Valley. The aim of this paper is to provide a broad overview of the ground condition present within the heritage zones and then link the evidence of the collapse and damages exhibited in ancient structures. This has been achieved by investigating the geotechnical characteristics of the soil supporting them and also by collecting associated damage evidence in the substructure and superstructure portion of the monuments. To achieve this goal, a team of engineers from Durham University and Newcastle University conducted a geotechnical site investigation and also performed reconnaissance survey to study the structural damage patterns at five heritage sites in Kathmandu.

2 GEOTECHNICAL INVESTIGATION

Field investigations was conducted during December 2017 and May 2018 within the five Heritage sites in the Kathmandu Valley with an aim to understand the local soil profile and collect more detailed information about the effect of the earthquake. A borehole was drilled at each location by cable percussion drilling after carefully recording and removing the archeological materials present from the ground level. Table 1 provides the details of the location of borehole and the termination depth for each of the borehole at different sites. A 10 m drilling was carried out to obtain the penetration resistance by performing Standard Penetration Tests (SPT) in the borehole at 1.5 m depth intervals during excavation and soil samples were recovered for laboratory testing to understand the geotechnical characteristics of the soil supporting the heritage structures. Figure 2 shows the ongoing drilling operation at the Pashupati site, pit created during archaeological investigation and the collected disturbed and undisturbed samples. Laboratory testing included particle size distributions, Atterberg limits, specific gravity and density were conducted in accordance with BS1377 (BSI 2016) at Geotechnical Laboratory of Durham University of United Kingdom on the transported soil samples. For some of the sites, testing was conducted to obtain the shear strength parameters of the soil, and modulus reduction and damping ratio curves of the soil.

Table 1. Details of borehole excavation conducted within World Heritage monument zones and Jaisidewal location of Hanuman Dhoka zone

Sr. No.	Location	Latitude and Longitude	Borehole termination depth (m)
1	Pashupati	27°42'37.47"N,85°20'55.23"E	12.43
2	Bhaktapur	27°40'19.43"N,85°25'41.50"E	11.07
3	Changu Narayan	27°42'58.59"N,85°25'40.41"E	11.40
4	Jaisidewal	27°42'0.44"N, 85°18'15.30"E	12.70
5	Hanuman Dhoka	27°42'14.54"N,85°18'23.93"E	13.60

Note: Boreholes of depth 10 m were terminated at different depth due to the presence of cultural materials at the site.

Figure 2. Pashupati location on December 10, 2017 (a) drilling operations, (b) removal of cultural materials (c) extracted disturbed sample and (d) undisturbed soil samples

At Pashupati site, soil was primarily sandy and SPT value ranged from 33-50 for the full depth of borehole indicating the presence of dense to very dense sand with a thin layer of medium dense sand at 8 m depth (SPT-N= 15). The soils were primarily non-plastic. Bhaktapur site showed nearly increasing penetration resistance ranged from 2-35 having very loose strata present at the shallow depth to very dense layer present at deeper depth. The soil was primarily clayey silt with plasticity index ranged from 4-12. Changu Narayan showed the presence of dense clayey silt having SPT-N ranged from 35-50 and plasticity index ranged from 6-12. At Jaisidewal location, SPT-N ranged from 8-50 indicating the presence of soft to stiff soil. The plasticity index of the soil ranged from 6-22 indicating the presence of clayey strata. Hanuman Dhoka revealed the presence of loose to medium dense to very dense sand strata where SPT-N ranged from 9-50 with a very thin layer of very loose strata at 7.5 m depth (SPT-N= 3). The specific gravity of the soil ranged from 2.55-2.72 indicating the absence of organic matter. More details about the geotechnical properties of sites can be found in Kumar et al. 2019 and 2020. During the drilling operation, the ground water table was only recorded at Pashupati at a depth of 7 m from the ground level. The drilling location at Pashupati was very close to the Bagmati river. It has to be pointed out that the drilling was carried out during the dry season. Also, the evidence of liquefaction was not observed at any of the surveyed heritage sites. Gautam et al. (2017) presented the evidence of soil liquefaction and lateral spreading in the neighboring areas of the heritage sites. The presence of dense granular strata at Pashupati site and dense strata at Changu Narayan site indicate a lesser possibility of seismic wave amplification whereas layers of soft strata present at Jaisidewal, Bhaktapur and Hanuman Dhoka might increase the influence of local site effect in amplifying the ground motion and period lengthening of the response spectrum. This was also evident from an extensive damage observed within the Hanuman Dhoka Durbar and Bhaktapur durbar square monument zones and minor damage observed at Chang Narayan monument zone. Similar evidence of damage has been reported by Shakya et al. (2014) during 1934 Nepal-Bihar earthquake.

Table 2. Details of soil types within World Heritage monument zones and structural damage

Sr. No.	Location	Geotechnical Characterization	Structural damage
1	Pashupati	Dense to very dense sand	Partial damage
2	Bhaktapur	Clayey silty to sandy silt	Extensive to partial damage
3	Changu Narayan	Silty sand	Partial damage
4	Jaisidewal	Top clay layer followed by silty sand	Complete collapse
5	Hanuman Dhoka	Silty sand	Complete collapse to partial damage

2.1 *Results of laboratory testing on Jaisidewal site*

Jaisidewal drilling location is located within the Hanuman Dhoka Durbar Square monument zone. During the earthquake, the area recorded complete collapse of 12 heritage structures including the oldest Kasthamandap and 325-year-old Jaisidewal temple. Hence, detailed geotechnical investigation was carried out at this location that included monotonic triaxial testing and cyclic triaxial testing on the undisturbed samples collected during the drilling operation to obtain the shear strength parameters and the dynamic properties of the soil.

2.1.1 *Monotonic triaxial testing*

Soils at Jaisidewal sites was clay up to 5 m depth followed by layers of silty sand at deeper depths. Monotonic undrained consolidated tests to an effective confining pressure of 100 kPa, 200 kPa and 300 kPa were conducted on the undisturbed samples recovered during the drilling operation to obtain the shear strength parameters of the soil as per BS1377: 2016. The soil samples were reduced to 38 mm in diameter and 76 mm in height by carefully extruding them to a thin walled sample tube. To achieve saturation, the cell pressure and then back pressure were increased gradually while maintaining a constant differential pressure of 5 kPa. After each increment of cell pressure, Skempton pore-pressure parameter B value was checked to ascertain the saturation. The sample was considered fully saturated at the B value of 0.96 and above. Thereafter, the samples were isotopically consolidated to the consolidation pressure by increasing the cell pressure and maintaining a constant back pressure. Figure 3 shows the results of triaxial testing for the samples recovered from the depths of 9 m and 12 m respectively. Figures 3a & 3c show the plots of deviator stress-axial strain response of the soil at the effective confining pressure of 100 kPa, 200 kPa and 300 kPa. It can be observed that the peak values of deviator stress were obtained at axial strains of around 5% and the peak values increased with an increase in the confining pressure.

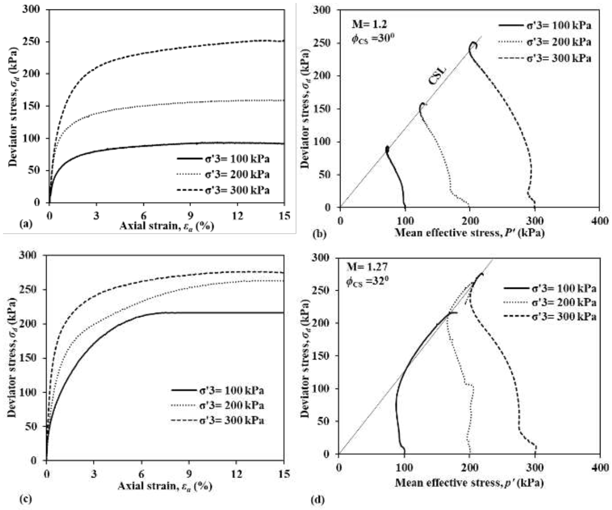

Figure 3. Results of monotonic triaxial testing (a) Deviator stress–strain response for silty sand at 9 m depth (b) Stress path and critical state envelope for silty sand at 9 m depth (c) Deviator stress–strain response for silty sand at 12 m depth (d) Stress path and critical state envelope for silty sand at 12 m depth.

Figures 3b & 3d shows the plots of deviator stress q and mean effective stress p' ($p' = \sigma_1' + 2\sigma_3'/3$) on q-p' space which was then used to obtain the critical state parameter M, the slope of deviator stress and mean effective stress. The critical state friction angle ϕ_{cs} was obtained using $M = 6 Sin\phi_{cs} / (3 - \text{Sin}\phi_{cs})$. The critical state shear strength friction angle for clay sample was obtained as 33^o, for silty sand at 9 m depth was 30^o and for silty sand at 12 m depth was 32^0. It was observed that the critical state shear strength friction angle obtained for different depths were comparable with shear strength parameters corresponding to SPT-values recorded during the drilling operation (Kumar et al. 2020).

2.1.2 *Cyclic triaxial testing*

To understand the response of soil under cyclic loading that would cause stress reversal during an earthquake event leading to degradation of its shear strength, laboratory undrained Cyclic Triaxial Tests were carried out on the soil samples retrieved during the boring process as per ASTMD3999 (2011). This test evaluates the dynamic characteristics such as shear modulus and damping ratio at high strain levels.

Figure 4 shows the recovered undisturbed sample from the very thin window-less cylindrical casing of diameter 80 mm to a 70 mm sample extruder and its placement on the triaxial base pedestal. Tests were conducted on samples of diameter 70 mm and height 140 mm. Saturation in the samples were achieved in the similar process of monotonic triaxial testing. Thereafter, the samples were isotopically consolidated to the consolidation pressure of 100 kPa by increasing cell pressure and maintaining a constant back pressure. The specimen was then subjected to 40 cycles of strain-controlled loading while maintaining a constant frequency of 1Hz. Figure 5 shows the representative result of cyclic triaxial testing conducted at effective confining pressure of 100 kPa and cyclic shear strain of 0.15% at a frequency of 1 Hz. Figure 5a illustrates the peak axial strain (ε_a= 0.3%) response of an undisturbed soil sample to 40 cycles of loading. Figure 5b represents the development of exponentially decaying deviator stress with an increase in the number of loading cycles which was mainly due to the generation of excess pore-water pressure. The cyclic deviator stress reduced to one-third of the maximum deviator stress with progressive increase in the cyclic loading indicating degradation in the strength of the soil. Figure 5c indicates the variation of deviator stress with respect to axial strain i.e. hysteresis loop that depicts the degradation of the stiffness of soil with an increase in the number of loading cycles. Figure 5d indicates the gradual increase in the excess pore water pressure ratio, r_u (ratio of excess pore pressure induced during shearing to an effective confining pressure, 100 kPa) where r_u reaches to a value of 0.65 at the end of 40 cycles of loading. Such increase in the pore-water pressure ratio was responsible for successive reduction in the deviator stress. The details about the modulus reduction and damping ratio curve of the soil can be obtained from Kumar et al. (2020).

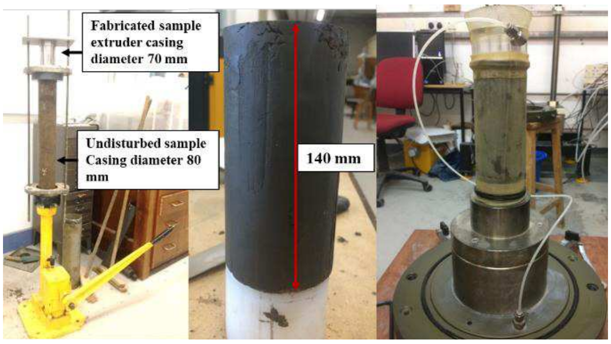

Figure 4. Undisturbed sample recovered using the sample extruder and its placement on cyclic triaxial test base padestal.

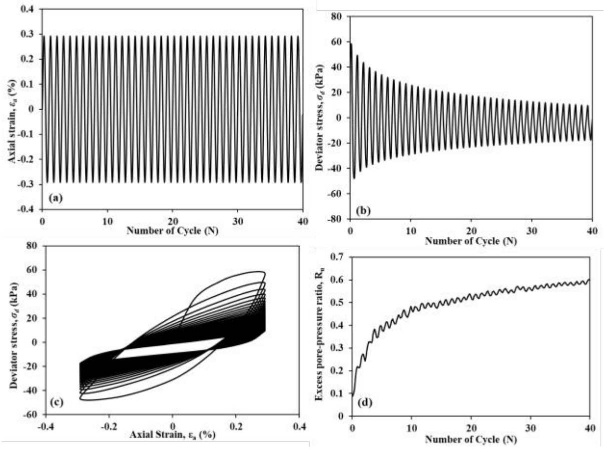

Figure 5. Cyclic triaxial test results: (a) Axial strain ε_a= 0.3%, f=1 Hz, σ_3'=100 kPa; (b) Deviator stress versus N; (c) Deviator stress verses axial strain ε_a; (d) PWP ratio r_u versus N.

The shear strength parameters of soil and the results of cyclic triaxial testing can then be used for conducting the in-depth analysis of the behaviour of heritage structures using the finite element modelling involving soil-structure interaction.

3 STRUCTURAL CONFIGURATION OF HERITAGE STRCUTURES AND THE DAMAGE EVIDENCE

Field reconnaissance survey was performed to study the types of the heritage structures and collect the damage patterns and document the damaged evidence. The monuments within the Kathmandu Valley i.e. three medieval urban centres of Lalitpur, Kathmandu and Bhaktapur as well as religious temples at Swyambhu, Budhanath, Pashupati and Changu Narayan were listed as UNESCO World Heritage sites in 1979 (Davis et al. 2020). They represent the development in the craft tradition of Nepal showcasing an excellent artistic style on timber, bricks, tiles and stones ((http://whc.unesco. org/en/list/121/). Structurally, these monuments were made of clay brick masonry with timber composites having roof covered with tiles which was mostly the feature of Nepalese Pagoda style temples.

The common structure typologies of a typical temple were symmetrical in geometric configuration which was resting on massive plinths usually 3-8 stepped plinth structures. Some of structures were made of stone masonry where almost all parts of the structure were made of carved stones. The brick masonry acted as a main load bearing walls of thickness ranged from 300 mm to 600 mm and roof of the cantilevered portion of the walls were typically resting on closely spaced wooden struts. Top of the temples were usually having a thinner cross section and roofing system was combination of timber structures and the roofing tiles. Figure 6 shows the schematic representation of a common Nepalese style Pagoda temple where the top portion, inner core and outer periphery of the temple structures can be seen. The top portion is having thinner cross section compared to the inner core and there is a column discontinuity where columns at the top are resting on crossing timber beams. The shade is usually provided as a protection measure during the monsoon season and the summer season. The masonry units were mud mortar which were composited with timber members.

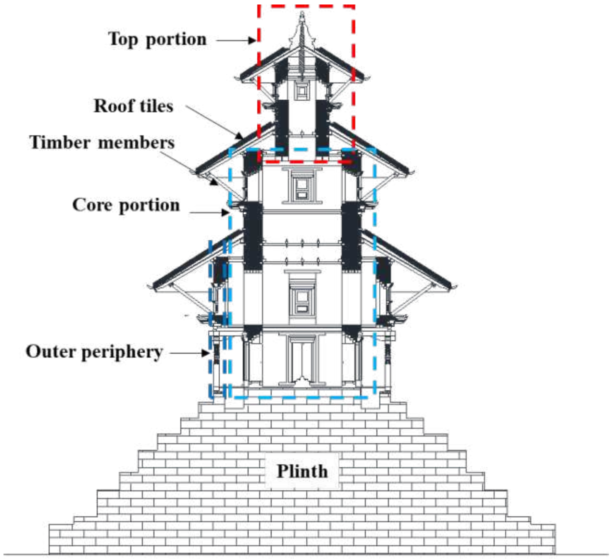

Figure 6. Schematic representation of a common Pagoda temple in Kathmandu Valley.

Although symmetrical geometrical configuration is better in terms of seismic standpoints, the column discontinuity is detrimental in distributing the inertia forces. The vertically and horizontally arranged timber members were connected with the masonry unit thereby providing stronger lateral stiffness against the seismic loading. However, age-related deterioration of the timber members and the connection joints were prevalent in these structures thereby undermining the lateral capacity. Also, masonry buildings are brittle structures in which mortar joints acts as plane of weakness because of low bonding characteristics of the mud mortar, which has extensively been used in Nepalese temple structures. Wall thickness varies between walls on different stories where outer wall was made of fired brick and inner walls were made of sun dried bricks. Inclined timber struts transfer the roof loads from tiled roofs to the masonry walls. The heavy massive roofing has the capability to attract larger inertia forces.

Experience has shown that masonry buildings are vulnerable and got affected more than reinforced concrete and timber structures under strong earthquake shaking (Augenti and Parisi 2010; Sarhosis et al. 2016). The large number of human fatalities in such constructions during these past earthquakes corroborates this. Acceleration and ground vibrations during the earthquake would induce inertia force in each of the stories and has potential to damage the structures if seismic demands are not met. It is important to note that some of these temples have survived the great 1934 Nepal-Bihar earthquake (M_w=8.1), 1988 Udaypur earthquake (M_w= 6.9) and 2011 Sikkim-Nepal Earthquake (M_w= 6.9). However, there are evidence of the collapse of the monument structures during 1934 Nepal-Bihar earthquake although the epicenter location was 160 km southeast of Kathmandu Valley indicating the seismic vulnerability of the heritage structure even in case of far-field earthquakes (Rana 1935).

During post-earthquake reconnaissance surveys conducted in 2017 and 2018, minor to serious levels of damage were identified in most of the structures surveyed. Figure 7 illustrates the typical symmetrical temple structures made of stone and brick masonry (Figure 7a) and the damage patterns within the arch of the brick masonry temple and a wide visible cracks within the walls (Figure 7c) and the view of dome shaped or stupa style temple structures (Figure 7d). Similar crack patterns were identified in many temples with similar geometrical configurations also constructed using brick masonry walls. This damage pattern is attributed to stress concentration near the crown portion of the temples and their inability to bear bending stress induced during seismic shaking.

Figure 7. Temple structures common typologies and crack propagation (a) View of symmetrical temple structures 3 years after the 2015 Gorkha earthquake (b) Crack propagation in the crown portion of a typical temple (c) cracks in the wall panel (d) Dome shaped temple structure.

Figure 8 show the distribution of crack within the temple structures where diagonal and vertical crack propagation can be observed in one of the temple structures of Bhaktapur and Hanuman Dhoka, and also the view of Changu Narayan temple showing no noticeable damage. It has to be pointed out that Changu Narayan Temple structure did not suffer damage even during the 1934 Nepal-Bihar earthquake. This may also be due to the location of the Changu Narayan on the hill top and the presence of very dense soil strata. However, some of the structures which has shown damaged evidence in the Hanuman Dhoka and Bhaktapur monument zones have wooden sculptures embedded within the masonry walls which has provided a zone of stiffness incompatibility and the zones of crack opening (Figure 8a). Such insertion of sculptures within the walls should be avoided in terms of seismic standpoints. In addition, the diagonal and vertical crack originating from the walls may be due to the inability of the walls to withstand the shearing action arising during the earthquake (Figure 8b). This may also be due to the inability of the mud-mortar present in the masonry walls to resist the lateral forces induced by 2015 Gorkha Earthquake. However, other portions of the building appeared to be intact from outside and the wooden support system are fixed and repair process were undergoing. Inspection within some of the heritage structures revealed flexure crack propagating from the timber connection points. In some of the structures, wide cracks ranged from 50 mm – 200 mm were observed which is difficult to repair. The survey noted minor level damage in the structure made of stone masonry and stupa or dome shaped structures. One storied smaller temples performed relatively well compared to the multi-storied temples. This was probably due to the fact that small temples developed good box action between all the elements of the building and in particular that of the roof and walls.

Figure 9 shows the view of the complete collapse of a temple structure within the Hanuman Dhoka Durbar square zone and the adjacent structures. It can clearly be observed that the adjacent structures made of modern construction materials performed very well compared to the masonry structures. Survey also noted that that the heritage structures were more affected as compared to modern reinforced concrete structures. Damaged evidence pointed out that the age-related deterioration of the construction materials, loosening of the bonding of the masonry units, poor connection within the composite structures and discontinuous loading distribution pattern along with local site effect might be responsible for the cultural catastrophe observed in the Kathmandu Valley.

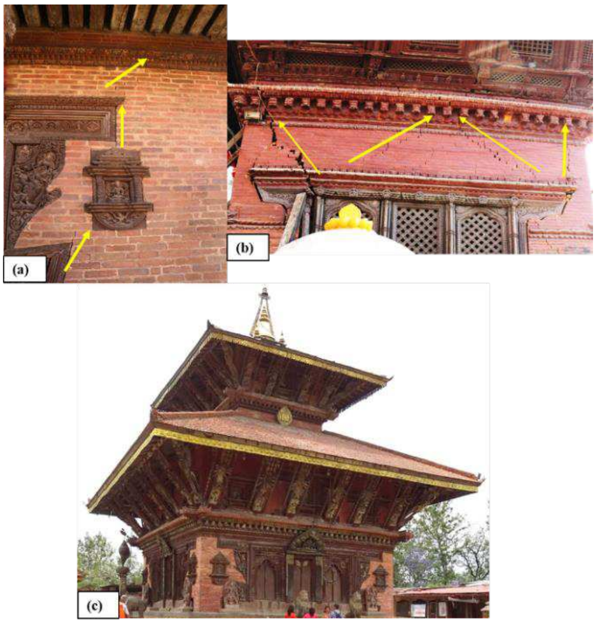

Figure 8. Masonry temple structure performance observed during the survey (a) Crack distribution in one of temple of Bhaktapur, (a) Crack distribution in one of the temple of Hanuman Dhoka, (c) view of Changu Narayan temple where no noticeable damages observed.

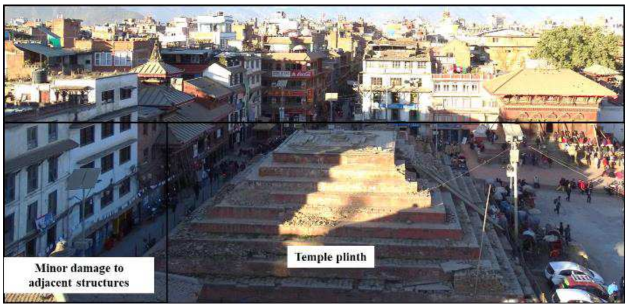

Figure 9. Complete collapse of heritage temple structure and minor level damage to adjacent structures made of modern construction materials.

The possibility of rotation and differential settlements in the foundation components of these structures were also explored during the reconnaissance survey. However, no evidence of such movement was identified by the team. Restoration works were ongoing in many structures with an aim to rebuild and preserve their ancient architecture.

4 CONCLUSIONS

This study tried to present the causes of the severe damage of the heritage structures observed within the World heritage monument zones of the Kathmandu Valley after the catastrophic 2015 Gorkha earthquake seismic sequence. This was achieved by investigating the geotechnical characteristics of the sites and understanding the damage mechanism of the collapsed and partially damaged structures. The information collected during the field missions and the laboratory testing were integrated to understand the high level of damage within the heritage structures. The soils present at the sites were mainly silts and sand with an exception of clay layers present at Jaisidewal and Bhaktapur location. The presence of dense soil media at Pashupati and Changu Narayan site inhibits the chances of seismic wave amplification however other sites may have experienced the effect of local site effect in terms of period lengthening and amplification. The extensive damage observed at Hanuman Dhoka Durbar Square corroborated this. The absence of groundwater at shallow depth also lowers any potential for soil liquefaction. No evidence of excessive total or differential settlements in the foundations of the structures was observed. The out-of-plane collapse noted in some of the structures was due to their inability to resist the lateral forces induced by the recent earthquake. Damage was also observed in the crown portion of most of the small temples due to stress concentration at the crown level and also the lack of a mechanism to provide bending stiffness during an earthquake event. The results of shear strength testing of soil and cyclic triaxial testing can be used for performing site-specific ground response analysis and numerical modelling involving soil-structure interaction that would be useful to understand the damage mechanism in more detail. In summary, the primary cause of damage in these structures appeared to be associated with lack of regular maintenance, inadequate bending and shear stiffness of the masonry walls and the local site effect. To safeguard these structures from future earthquakes, it is suggested that periodic inspection and maintenance of existing archeological infrastructure would increase the seismic resilience of these structures. A repair process should be carefully chosen considering the global seismic response of the buildings where added mass in addition to constructing only collapsed portion of the structure may provide a weaker zone and would create localization of the internal stress resultants within the structural members.

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