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**Reducing Disaster Risk to Life and Livelihoods by Evaluating the Seismic Safety of
Kathmandu's Historic Urban Infrastructure: enabling an interdisciplinary pilot**

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Abstract

Kathmandu's medieval cities and shrines are exceptional architectural and artistic achievements underpinned by centuries of seismic adaptation. They host urban infrastructure of tangible and intangible value and play vital roles of cohesion in the life of thousands of people. They also represent portals where the heavens touch earth and individuals can commune with guiding deities. The 2015 Gorkha Earthquake and its related aftershocks were a human disaster, killing 9,000 people and displacing 2.8 million from their homes. Generating 7.6% of Nepal's GDP through tourism, Kathmandu's iconic skyline was dramatically altered by the earthquake. It destroyed 500,000 homes and undermined the sustainability of Nepal's tourist industry and its 400,000 employees. However, it was also a cultural catastrophe damaging 403 monuments in Kathmandu, key elements within the Valley's historic urban infrastructure. Their collapse caused multiple fatalities and first

responders demolished others fearing that they might also fall and injure residents and visitors. With Overseas Development Assistance pledges of \$2.5 billion US dollars, Nepal's Government approved the rehabilitation of much of Kathmandu's historic infrastructure but there is continued tension between interpretations of Sendai's 'Build Back Better' framework and the obligation to preserve the authenticity and intangible values of its UNESCO World Heritage Properties.

Many risk reduction strategies implemented in Kathmandu are demolishing historic buildings and rebuilding them in modern materials; while other monuments have been hybridised with metal bracing or concrete reinforcement. Mud mortars are frequently being replaced by cement and lime, although the resultant inflexibility is not necessarily seismically advantageous. Many monuments have been, or are being, demolished and rebuilt without research and analysis of why they collapsed. Even their foundations which in many cases preserve sequential experimental adaptations offering examples of practical seismic-resistant foundations, which could be applied to other structures, are being removed without record or research. With donor liability fears, contractors privilege modern materials, despite successful histories of vernacular systems. Costly historic bricks have been landfilled, causing supply chain delays and increased environmental impact from kilns. Residents, craftspeople and tour operators and businesses have been frequently excluded from decision-making but the risk to them, and their livelihoods, remains. Building on an interdisciplinary north-south partnership, we have piloted the integration of archaeology and geoarchaeology with 3D visualisation and geotechnical and structural engineering to co-produce and disseminate methodologies to assess, evaluate and improve the seismic safety of historic urban infrastructure within Kathmandu's UNESCO World Heritage Properties, reducing direct risk to life and livelihoods, while respecting and preserving Kathmandu's authenticity and traditions and, in some cases, revitalising them.

Key Words

Nepal, Kathmandu Valley, UNESCO World Heritage, Earthquakes, Historic Infrastructure, Urban Infrastructure, Resilience, Risk, Sustainable Development Goals

Introduction

On the eve of Kathmandu's Saraswati *Jatra*, or festival of the Goddess of Wisdom, members from one of the four city wards neighbouring Maru Tol at the south-west end of Hanuman Dhoka's Durbar, or Palace Square, met together outside the Police Station on the morning of Saturday 9th February 2019. As they filed into the station yard within the UNESCO World Heritage Monument Zone, the 32 strong group selected and lifted one of the four 7 metre long timber columns on a rope sling attached to a bamboo carrying cradle and carried it towards Maru Tol (Figure 1). Straining against a weight of one and a half tons, they then approached a scaffold of some 400 bamboo poles tied together with jute ropes, which had taken two weeks to construct, and positioned it near the north-west saddlestone of the newly restored foundation plinth of the Kasthamandap, the city's eponymous monument. The following morning of the Sarawati Puja, ceremonies were focused on the column before it was lifted into its saddlestone. The other three columns were subsequently brought from the station yard for a larger celebration as the Kumari, one of Kathmandu's living child goddesses, observed and sanctified the event amongst crowds and traditional music (Figure 2). All four columns were lifted into place in the same afternoon as the tenon at the base of each was placed just over the ancient mortice joint cut into each of the saddlestones below. Teams of 32, again drawn from the neighbouring wards, pulled ropes that were slung over the

bamboo scaffolding and tied to the top of the posts to complete the joining of the timber superstructure to the brick foundation plinth. Later, the capitals and crossbeams were pulled up the bamboo scaffold ladder and reunited with the columns with the use of tenon and mortise joints.

These events were keenly watched by the interdisciplinary team of engineers, architects, archaeologists, heritage managers and community leaders who made up the Kasthamandap Reconstruction Committee, and accompanied by religious ceremonies of Vajrayana and Hindu tradition. All were now aware that these communities were enacting a similar event which last occurred a millennium ago when the monument believed to have given Kathmandu its name, Kasthamandap is literally the Sanskrit for ‘wooden pavilion’, was erected. What is most remarkable about this modern event is that many of its lessons and practices were learnt from the painstaking analysis of the ruins and rubble of the monument when it collapsed in the Gorkha Earthquake on 25th April 2015 when over 70 lives were lost as it hosted a temporary blood donation clinic. These discoveries demonstrated that the study of the past, even within a post-disaster environment, can help inform the present and act as a catalyst for communal resilience and pride. In the words of Rajesh Shakya, Chairman of the Kasthamandap Reconstruction Committee and newly elected by Kasthamandap’s wards as Member of the Provincial Assembly of Nepal’s new Province 3, ‘The Kasthamandap has proved the importance of archaeological and scientific studies, especially for those cases where history and culture are embedded below the surface’.

Mr Shakya’s words in February 2019 demonstrate the realisation of the ambitions of a group of over 180 heritage experts, professionals and stakeholders who met at the ‘Heritage at Risk 2017: Pathways to the Protection and Rehabilitation of Cultural Heritage in South Asia’ Workshop in Kathmandu between the 4th and 7th September 2017 (Coningham and Lewer 2019). Drawn from across South Asia and beyond, and coming from a wide range of

disciplines, including conservation, planning, heritage management, economics and development, architecture and archaeology, they had discussed contemporary issues of the protection of heritage during natural disasters and conflict with community members, army, police, site managers and policy makers (Figure 3). Supported by UNESCO's Kathmandu Field Office, ICOMOS (Nepal), the Department of Archaeology (Government of Nepal) and Durham University's UNESCO Chair, the AHRC-GCRF funded delegates co-produced a number of key resolutions for the enhanced protection and rehabilitation of heritage following disasters. Of their 15 key points, many of which reiterated the Department of Archaeology's 'Conservation Guidelines for Post-2015 Earthquake Rehabilitation', four are particularly relevant to this paper:

A5. Multidisciplinary teams of archaeologists, engineers, architects, environmental scientists, cultural historians and conservators, should undertake a sample of evaluations of collapsed and damaged monuments to identify the causes of their failure. The sensibilities and beliefs of the related communities shall be taken into account.

A7. Appropriate research, including rescue archaeology and investigations of seismic safety, shall be carried out to improve the knowledge on the historic structure which will contribute to the significance as well as serve as the basis for planning out conservation or restoration interventions. There is a need to establish a clear methodology for evaluating the seismic safety of historic monuments and scientific research on materials in order to prioritise rehabilitation or strengthening and reduce risk to life and livelihoods.

A13. Every archaeological assessment and excavation process should be linked in a coherent and integrated approach with community consultation and engagement. This should be implemented through the development of a long-term sustainable partnership and shared custodianship.

A15. There is an urgent need for targeted exchanges and training, with the adoption of training materials, to strengthen the capacity of South Asian national agencies and NGOs tasked with the protection and rehabilitation of sites and monuments following natural and cultural disasters as well as conflict. This should be accompanied by an awareness program on the protection of monuments and heritage sites for community and security personnel. Mechanisms for the sharing, coordination and archiving of methodologies and outcomes from bilateral programmes of protection and rehabilitation should be urgently prioritised.

[\(https://www.dur.ac.uk/cech/unescochair/workshops/heritageatrisk/kathmanduresolutions/\)](https://www.dur.ac.uk/cech/unescochair/workshops/heritageatrisk/kathmanduresolutions/):

Building on these co-designed and agreed resolutions, an interdisciplinary North-South partnership was brought together under the British Academy's GCRF Cities and Infrastructure Programme (CI170241). This partnership aimed to pilot the integration of archaeology and geoarchaeology with 3D visualisation and geotechnical and structural engineering to co-produce and disseminate a methodology to assess, evaluate and improve the seismic safety of historic urban infrastructure within Kathmandu's World Heritage sites with the ambition of reducing direct risk to life and livelihoods, while preserving Kathmandu's authenticity and traditions. This article, reviews the enabling of that partnership and the immediate impacts, one of which has already contributed towards the rebuilding of the Kasthamandap.

The Interdisciplinary Pilot and its Methodology

The main motivation of the Kathmandu 'Heritage at Risk 2017' Workshop and the newly formed interdisciplinary team was to educate and avoid a continuation of the irreversible destruction of urban heritage both during the Earthquake itself but also after the emergency.

The former destruction referenced the clearance of protected monuments within Kathmandu's UNESCO World Heritage Monument Zones, where bulldozers and JCBs had been used by first responders to clear the streets of debris as well as to assist with the recovery of the injured and dead from collapsed monuments (Figure 4). Our later post-disaster archaeological interventions at the Kasthamandap in Hanuman Dhoka demonstrated that about one third of the entire monument's foundations had been irreversibly damaged by the mobilisation of such heavy equipment, which cut through floor surfaces where individuals may have been trapped. Rather than attempting to recycle the medieval brick and tile, these materials were piled with modern concrete and bricks and dumped in landfills, creating bottle necks for the later production of bricks of the correct quality and strength. Of direct economic significance, each dumped brick cost £1.31 to replace, before calculating the economic cost of the firing process. While such damage is understandable during the immediate emergency, what is less acceptable were the later numbers of exploratory trenches dug by architects and engineers into the foundations of monuments across Kathmandu's UNESCO World Heritage Monument Zones without the presence of archaeologists or any recording after the emergency (Coningham et al. 2016). This approach was particularly striking at Patan, where the Mani Mandap was systematically destroyed over a period of months and rebuilt without any scientific research, recording or analysis of its foundations or the cause of collapse. Indeed, the architects involved merely claimed that the archaeological soils and sediments removed with the foundations were just 'trash' (Ranjitkar 2016: 306). Moreover, the indiscriminate drilling of soil cores across the Kathmandu Valley World Heritage Site also demonstrated a clear lack of understanding of the historic subsurface fabric beneath the streets of Kathmandu (Coningham et al. 2016), so clearly demonstrated by our use of Ground Penetrating Radar in 2015 and 2016.

Perhaps as significantly, our earlier post-disaster 2015 and 2016 missions to Kathmandu, funded by UNESCO, AHRC-GCRF and National Geographic, had demonstrated that in many cases when the superstructure of monuments had collapsed, the substructure had not sustained significant earthquake related damaged or distortion. This was particularly demonstrated by the excavation of the ruins of the Kasthamandap in Hanuman Dhoka, where previously there had been several architectural studies of its timber superstructure, yet nothing was known about its foundations (Korn 1976)(Figure 5). Our excavations at the Kasthamandap were initiated to understand its construction, identify causes for collapse and to provide evidence about the foundations for engineers and architects tasked with the monument's reconstruction. Once we had cleared away the rubble, we were able to confirm that the Kasthamandap's original foundations were monumental with brick walls two metres deep set in mud mortar. Forming a square of 12 by 12 metres, these foundations enclosed four massive brick piers at the centre of the building, each two metres in height. Four large saddlestones cut with mortice sockets were laid above the piers and 16 double saddlestones above the foundation wall, into which the three-storied timber superstructure was supported and locked. This massive core was then surrounded by an outer wall measuring 18 by 18 metres. We have been able to date the construction of the Kasthamandap's brick piers and foundation walls to c.700 CE using Optically Stimulated Luminescence Dating (OSL). This monumental construction was then subject to major remodelling 200 years later when thin bracing walls one brick thick were constructed between the piers and the inner foundation wall (Figure 6). These results confirm that the Kasthamandap was built almost 500 years earlier than its first mention in historical texts and had survived numerous earthquakes (Coningham et al. 2018).

The resulting pattern of foundation and bracing walls formed a nine-celled mandala, also found in other monuments within the Kathmandu Valley, such as at Harigaon (Verardi 1992).

Our investigations of the central cell of the layout revealed the presence of another nine-celled mandala below the central sanctum. Furthermore, we recovered gold foil mandalas within the mortice sockets of each of the four central saddlestones, highlighting the intangible heritage associated with monumental construction in the Kathmandu Valley. Of symbolic value, the foundations and bracing walls clearly formed part of the seismic resilience of the Kasthamandap. Set in mud mortar, this material offered flexibility during seismic events and saved the building from greater stress. Originally constructed in c.700 CE, its foundations display remarkable resilience over centuries of earthquakes and our research has identified that the majority of damage caused to its foundations was caused during the emergency phase immediately after the 2015 Gorkha Earthquake but also that the monument had been weakened during earlier conservation interventions.

Indeed, while clearing rubble from the Kasthamandap in 2015, we identified that one of the four large central saddlestones around the central Gorakhnath shrine was missing. This was surprising as its postulated location, in the north-east, was covered by tiles without a socket to support the timber beam which had stood there (Figure 7). We later confirmed its presence in 2016 as we removed the tiling, allowing us to refute our earlier concerns that the missing saddlestone might have collapsed or sustained damage in earlier seismic events. Once the surface of the saddlestone was cleaned, we confirmed the presence of residue indicating that a copper plate had rested above its socket, as already recorded on the other three saddlestones in 2015. These plates separated the timber beam of the superstructure from the stone and brick foundations, potentially acting as a damp course to protect the timber elements of the structure. As importantly, we recovered the corroded remains of a copper shoe around a fragment of degraded timber tenon from within the socket. Originally attached by nails, the copper sheeting protected a replacement tenon, which had been added to the base of the timber pillar. The master craftsmen associated with its reconstruction suggested that the

copper oxides associated with the plates may also have acted as a deterrent to termite ingress. When the Kasthamandap was repaired in the 1960s, its conservators had discovered that the replacement tenon in its shoe had also rotted but, rather than replacing it, pushed it into the socket below and tiled over the saddlestone. We recorded evidence of similar practices under other major timber elements, whose saddlestones had just been filled with cement, confirming that the integrity of the tie between foundations and superstructure had been weakened. Contributing factors in the Kasthamandap's collapse, its timber pillars were free-standing and potentially moved at a different rate from the rest of the structure, despite its extremely resilient foundations. The absence of seismic damage to the Kasthamandap's foundations is a feature found at other monuments around Hanuman Dhoka, whose foundations have been equally resilient. It is therefore likely that centuries of experimentation of the locking of timber superstructures into foundations of brick in mud mortar have led to a resilience whereby many examples of collapse and damage can be attributed to modern conservation interventions, including the use of modern materials such as cement, and poor maintenance. However, we were aware that results from subsurface investigations would need to be more engaged and linked to superstructure designs, as well as the properties of underlying natural soil profiles.

In this context, our interdisciplinary north-south partnership aimed contribute to SDG17 by co-producing and disseminating a methodology to assess, evaluate and improve the seismic safety of historic urban infrastructure within Kathmandu, reducing risk to life and livelihoods while preserving Kathmandu's authenticity and intangible traditions, thus contributing to SDG11, inclusive, safe, resilient and sustainable cities. Our methodological ambition was to co-produce a 'heritage ecosystem' approach by combining geotechnical and structural engineering with geoarchaeological and archaeological outcomes from a sample of monuments within Kathmandu's historic infrastructure. Our team thus set out to assess

historic construction practice, and traditional construction ability, and pilot the mapping of them onto rebuild initiatives with the objective of improving, and where appropriate, blending with modern low interventionist retrofitting strategies. We are currently engaged in the final analysis of construction materials, introduced cultural soil foundations, brick, mortar and timber attributes, augmented by reanalysis of soil cores to model site amplification and earthquake motion. As many superstructure elevations were incomplete, we also undertook to create 3D reconstructions from Multi-View Stereo/Structure-From-Motion photogrammetry with other contextual information integrated into a modified Potree viewer, combining extant photographic records, crowd-sourced imagery and web-scraping.

We worked with Nepali experts in vernacular systems to better evaluate issues of seismic performance, damage and progressive deterioration from shock and aftershock sequences. Working with a sample of residents, craftspeople, tour operators and businesses, we also began to record traditional processes of procurement, construction, recycling and maintenance, and the intangible value of individual monuments as well as patterns of spend and behaviour. Whilst not yet fully implemented, we also devised a strategy for the sharing and dissemination of our approach and methodologies.

Geophysical Survey and Risk Mapping

As noted above, our earlier UNESCO and AHRC-GCRF sponsored fieldwork in the aftermath of the 2015 Gorkha Earthquake had allowed archaeologists from the Department of Archaeology (Government of Nepal) and Durham University's UNESCO Chair to use Ground Penetrating Radar survey to demonstrate the spread and depth of subsurface heritage under the paved Durbar Squares of Hanuman Dhoka, Patan and Bhaktapur to policy makers, planners and residents (Figure 8)(Coningham et al. 2016). Accompanying the geotechnical

coring associated with the British Academy's GCRF Cities and Infrastructure Programme, we undertook additional survey with a Mala 500 MHz system, mounted on a rough terrain cart, measuring vertically downwards. The present report is based on the preliminary investigation of data using an estimated ground velocity; the depth ranges mentioned may therefore have to be revised after full evaluation. All surveys were undertaken within local geophysics grid coordinates and grids were established and measured using a Leica Robotic Total Station.

During our survey of the largely empty courtyard of the Changu Narayan Temple, we identified a series of interesting anomalies in the south-east, close to the selected location of the excavation trench. These comprised two 1.5 metre wide linear anomalies running north to south and represent the remains of collapsed walls, or foundations below the modern courtyard. The eastern of these appears to have been cut by modern drains, again illustrating the modern damage to such subsurface heritage. Just east of the main entrance to the compound, there are rectilinear anomalies enclosing an area of approximately five by five metres. The team was also invited by the city's Member of Parliament to undertake geophysical survey at Bhaktapur's Shree Padma Secondary School. The entrance to the school is fronted by a pair of stone lions, similar to those in front of the main palace at the Durbar Square and this feature had suggested to a number of historians that the school was built on top of a demolished part of the palace complex. The survey yielded anomalies around the area selected for the excavation trench and, just to the north of the volleyball field and south of the adjacent brick building, it identified the presence of a three metre wide row of rectangular 'rooms' at a depth of c. 0.6 metres. Their location correlated with a step in the topography, probably caused by the linear brick structure beneath. Further south, running west to east through the middle of the volleyball field, a strong 2.0 metre wide anomaly was identified, probably the foundation of a substantial wall. It is pierced by a 4.4 metre wide opening that might have been a gate and, to east of the opening, there are some broadly

rectangular cells, at a depth range of between 0.7-1.3 metres, are visible. These results, suggested that the community memory of the location of the long lost palace was correct and but that this subsurface monument is vulnerable to redevelopment on the surface.

Survey was also undertaken in Hanuman Dhoka's palace complex, within its open courtyards to ascertain the presence of structures below the paving. Unfortunately, considerable parts of the first courtyard, Nasal Chok, were still covered by scaffolding and were therefore not accessible for GPR surveys. In the vicinity of the scaffolding, data quality was affected and there, especially at deeper layers, anomalies are more difficult to evaluate. The most notable features are the 'negative' anomalies that are visible in the data. In contrast to the usual appearance of structural remains, 'walls', as high reflections (black in the time slices), these appear as low reflections (white in the time slices). They are interpreted as trenches from which wall foundations have been removed in the past. Amongst these there are four anomalies in particular, which can be identified. Three are to the north of the platform: a square outline of 4 metre side length and two small squares of 1.5 metres side length. These could be the foundations trenches of former small shrines. Protruding from the eastern edge of the platform is a semi-circular fourth anomaly; it is reminiscent of a removed semi-circular stone. In addition, there are several areas of high reflection strength throughout the courtyard, which could be platforms.

The second was Dakh Chok, which lies to the west of Nasal Chok. It was covered with several piles of building materials and the damaged walls of the surrounding buildings were supported by wooden beams that reach into the courtyard, some of which were fixed to the courtyard's floor with steel rods. The floor of the courtyard was well made, with a slight slope from the centre to the outer perimeter. The paving slabs were carefully shaped to create an interlocking pattern, incorporating a number of saddlestones. The survey data show various anomalies, some clustering together, for example in a dice-like figure-of-five

arrangement. However, whether these spatial relationships persist over an extended depth range is not yet clear. To the south of Dakh Chok, the team also conducted survey in Lam Chok and identified a narrow linear anomaly, running east to west, between 0.5-0.7 metres deep and most likely represents a modern utility. Another linear east-west running anomaly, more substantial and slightly deeper, can be seen in the middle of the courtyard; it could represent the foundation of an earlier subdivision wall. We also conducted survey outside the palace complex, including the site of the soil core on the platform beside Jaisidewal Temple. Here, we identified several anomalies underneath the platform. To the west, there were three thin parallel anomalies, running east to west. Whether they are very thin walls or utility pipes is as yet unclear. An area of high reflections extended south and east from the excavation trench location. It stops for 2.1 metres and then continues to the eastern edge of the platform.

These results reinforced the fact that the standing remains of Kathmandu's urban architecture are only the most recent phase of multiple remodelling of space and structure, presumably as patrons exploited opportunities offered by earthquakes and aftershocks. The final geophysical survey focused on Bhaktapur's famous Nyatapola Temple in Taumadhi Square. The five storey temple is located in the north of the square and comprises four steps or plinths with one additional platform to the south. The temple did not experience notable damage during the 2015 Gorkha Earthquake. The circumference of the first plinth of temple was investigated over a width of 2.3 metres with a line spacing of 0.15 metres. The data show some internal curvilinear structures and some anomalies likely to be caused by large rocks. Significantly, there was no sign of cross-connection between the walls, that is, no connection between the outer wall of the plinth and the wall of the next plinth. Given the clear signals from other internal features, this must be interpreted as strong indication for the absence of internal cross-connections. In the light of the temple's resistance to earthquake damage, this design feature is interesting and confirms earlier results from our post-disaster rescue

archaeology season when we confirmed that a number of the Kathmandu Valley's multi-plinth temples were comprised a solid central brick plinth with a series of less formally constructed step plinths around it.

Our GPR surveys have led to the co-production of Archaeological Risk Maps to assist site managers guide development. This involved the generation of maps of potential subsurface features across Hanuman Dhoka, Patan and Bhaktapur within a traffic light system of Red, Yellow and Green – Red being associated with most risk to subsurface heritage and Green the lowest. The map of designated areas was accompanied with recommendations to help guide physical planning, facilitating the development of an awareness for the protection of subsurface heritage whilst not being of detriment to the rehabilitation of essential services (Figure 9). Current plans by the Asia Development Bank to cut a major sewer line through the World Heritage Monument core at Patan are currently being adjusted, based on these Archaeological Risk Maps, to ensure that the vulnerable subsurface heritage identified there will not be irreversibly destroyed. Archaeological Risk Maps for the sites surveyed as part of the British Academy GCRF Cities and Infrastructure sponsored fieldwork are now being developed.

Archaeological Excavation

Our GPR surveys thus had already indicated the presence of subsurface heritage below the current ground surface at sites identified for multi-disciplinary investigations during the British Academy's GCRF Cities and Infrastructure programme. As previous archaeological rescue and research excavations in the Kathmandu Valley after the 2015 Gorkha Earthquake indicated Kathmandu's rich, vulnerable and finite subsurface heritage was threatened by post-emergency interventions we decided first to excavate before coring. Indeed, excavations at

the Kasthamandap, Maju Dega Temple, Trailokiya Mohan Temple as well as Jagannath and Gopinath Temples in Hanuman Dhoka's Durbar Square, and the Char Narayan Temple in Patan's Durbar Square (Coningham et al. 2016), had all encountered evidence of earlier phases of settlement and construction activity. They also highlighted the complex biographies of monument development and evidence for the strength and resilience of traditional construction techniques and materials for seismically adapted foundations. Therefore, prior to any intrusive geotechnical investigations, small-scale targeted archaeological excavations were undertaken to provide systematically and scientifically recorded sequences down to the natural soil in advance of geotechnical analysis, preserving in record, and identifying earlier archaeological sequences, which would otherwise be damaged by drilling activities (Figure 10).

The opening of the archaeological trenches also provided the opportunity for geoarchaeological investigations, facilitating scientifically dated chronological sequences that could be linked to cultural and structural phases and artefactual typologies. At several sites, excavations also provided further opportunities to assess and evaluate the nature and condition of monument foundations. Our excavations identified deep archaeological sequences between one and three metres in depth at sites across the Kathmandu Valley. The shallowest sequence was within the courtyard at Changu Narayan Temple, where within one metre of cultural activity excavations identified levelling deposits overlaying an earlier brick paving and stone wall footing, which itself sat on an earlier phase of wall and pavement construction. At Gurujyu Sattal within the Pashupati complex, we uncovered evidence of stone and brick walls constructed later in the sequence, but sealed below the current paving at the site. Found below several phases of cultural accumulation and occupation, the earliest cultural activity at the site included a brick pavement constructed directly on the natural soil. The most complex sequence was identified at Bhaktapur, where within the grounds of the

Bhaktapur Shree Padma Secondary School, a series of structures was identified below a deep deposit of rubble levelling. This included an earlier brick lined tank, with associated drain, which was then infilled. A brick structure, with brick paving and saddlestones was built directly over the top of the infilled tank, and was then subsequently covered by levelling material. These constructions potentially link to earlier phases of activity associated with the Bhaktapur palace site located to the north of the Durbar Square.

Excavations adjacent to the Trailokiya Mohan Temple in Hanuman Dhoka identified earlier phases of temple construction, with the plinths of the latest phase of temple constructed directly on top of an earlier monumental wall construction. This earlier monument's foundations were constructed from brick set within mud mortar and exhibited no visible sign of seismic damage through evidence of Earthquake Archaeological Effects (Rodriguez-Pascua et al. 2011). This is a trend that has been identified at the majority of monuments investigated during post-disaster archaeological interventions (Coningham et al. 2018), but contrasts to evidence at Jaisidewal, where close to the collapsed temple, several phases of structures were identified, including paving above the natural soil. These structural phases provided evidence of tilting walls as well as shear cracks, all indicative of past seismic damage. The identification of these effects at Jaisidewal, as well as resilience at the majority of monuments assessed in the Kathmandu Valley, can be linked to evidence from geotechnical analysis to identify whether underlying local soil conditions had an effect on the seismic stability of monuments and structures in different areas.

From the excavations conducted at Bhaktapur, Changu Narayan, Pashupati, Jaisidewal and the Trailokiya Mohan Temple in Hanuman Dhoka's Durbar Square, it is clear that several complex phases of earlier cultural activity are present below the current ground surface, including areas that are now open spaces. Rather than the contemporary configurations of standing structures marking how the layout of these sites has always been, excavations have

shown that these later monuments, many with their above-ground architecture damaged by the 2015 Gorkha Earthquake, represent the very last phase of construction. It is therefore an imperative that any subsurface cultural deposits and features, which in places also form part of the UNESCO World Heritage Properties, should be protected from intrusive digging, or that rescue archaeological excavations or watching briefs should be undertaken if intrusive digging is required for the laying or repair of essential amenities. Furthermore, our excavations have uncovered vernacular and traditional materials and construction techniques, which can be analysed to understand centuries of development of seismic adaptation strategies from the past communities of the Kathmandu Valley up until the present. To reiterate earlier advice, Kathmandu's urban planners and heritage managers need to 'look down and not up' if this unknown heritage is not to be irreversibly destroyed! (Coningham et al. 2018).

Geoarchaeological Assessments

Our geoarchaeological assessments of monuments within the Kathmandu Valley's UNESCO World Heritage Site in the aftermath of the 2015 Gorkha Earthquake have focused on cultural significance and earthquake proofing by defining site chronologies, monument foundation deposits and structural materials from post-earthquake monument remains. Working at the interface of archaeological and engineering evaluations, geoarchaeology assessments have been found to offer new narratives for both the past and future of archaeological monuments in the seismically active Kathmandu Valley. Our approach has been systematic and experiential, working first with the Kasthamandap within Hanuman Dhoka's Durbar Square in 2015 and 2016 as a test bed for field and laboratory based analytical methods before extending to other monuments across the Kathmandu Valley as part of the British Academy's

GCRF Cities and Infrastructure programme. These monuments include the Vatsala in Bhaktapur; Changu Narayan; Gurujyu Sattal in Pashupati; and Trailokiya Mohan and Jaisidewal in Hanuman Dhoka's Durbar Square and environs. As noted above, excavations prior to the drilling of geo-technical boreholes has demonstrated that monument foundations are fired brick walls, set in mud mortar, with earth deposits between the walls; it is the earth deposits that are the focus of geoarchaeological investigations. Salvaged timbers from the monuments have also given further opportunity for (bio)-geoarchaeological assessments.

One of our foci has been the assessment of monument chronologies as the age(s) of individual monuments and their various parts is fundamental to understanding its evolution over time, including responses to seismic activity in the past and likely responses in the future. Given the soils- and sediments- based nature of monument foundations, we have developed Optically Stimulated Luminescence (OSL) measurement as a means of dating monument foundation sediments. Working with archaeological interpretations of foundation walls, we have sampled beneath main, cross and outer foundation walls and associated fills. Measurement of environmental dose rates in the field and laboratory together with laboratory based stored dose assessment based on single aliquot regeneration (SAR) sequences on quartz grains are integrated to give culturally related ages for foundation deposits. These have yielded age range clusters from c. 110 BCE through to the sixteenth century CE. We are complementing OSL chronological assessments with calibrated radiocarbon measurement of cores from salvaged superstructure timbers sediments. Following discussions with Nepali architects and architectural historians, we ensured that these samples included main pillars, cross-beams, and brackets. This work is currently restricted to one monument, the Kasthamandap, but has provided calibrated ages (95.4% probability) from fifth century to the twelfth centuries CE (Figure 11). Our chronological findings are recalibrating monument history in the Kathmandu Valley and offer new insight into foundations that are seismically

stable in contrast to other monuments where there is ongoing modification, including contemporaneous activity across a number of monuments. Timber superstructures also change with time, with major changes superimposed on earlier foundations and incorporation of earlier timbers into later constructions. Both foundation and superstructure change can be related to the social complexity of responses to seismic events.

Our focus on monument foundations has also intensified and our starting point has been the integration of documentary and environmental sources to generate hypotheses on foundation construction and to give a comparative control on geoarchaeological evidence. Dating from the sixth century CE, the *Bṛhatsaṃhitā* offers instruction on building architectures including materials and construction of foundations and indicates a diversity of materials from different sources might be expected in the Kathmandu Valley monument foundations. Environmental control has been obtained from a trench adjacent to the Kasthamandap, giving indication of fluvial sediment accumulations ranging from high energy coarse sand deposits through to clay deposits indicating low energy and intermittent river flows; foundation deposits are expected to contrast with these fluvial deposits. Geoarchaeological analytical methods applied to the analyses of the Kasthamadap foundation sediments are an integration of field-based Munsell colour, texture class, hand-held penetrometer (soil strength) and X-Ray Fluorescence (XRF), and laboratory-based particle size distribution (PSD) with follow-up speciation of the clay fraction through X-ray Diffraction (XRD) undertaken at Historic Environment Scotland, and thin section micromorphology with follow-up scanning electron microscopy and EDX. Analyses indicates foundation soils are distinct from the local early fluvial environment, have been introduced from a range of locations including industrial and agricultural locations, include layering of organic materials with associated ceramics and all organised as discrete horizons. They are an engineered soil respecting traditional practices

while giving a degree of liquefaction proofing by allowing water movement through the sediments.

Initial analyses of foundation wall mortars indicate strong similarity to the foundation sediments with early indications of a slightly raised non-swelling clay content and indicate a degree of liquefaction proofing. Analyses of structural timbers through microtome slicing, novel safranin stained fluorescence, auto fluorescence and confocal microscopy is permitting spectral imagery analyses that shows cell structure attributes together with cellulose and lignin levels. We are currently disentangling the complex relationships between timber species, radiocarbon age, decomposition attributes and timber strength. Current evidence suggests that some timbers decomposed from the inside out with others from the outside in; emerging analyses indicating decomposition patterns related to reduced timber strength.

We are providing new seismic-related biographies of monuments within Kathmandu's UNESCO World Heritage Properties that relate directly to universal value, authenticity and integrity criteria. In light of the cultural significance that monument foundations hold, we actively seek that their conservation and protection be a priority in any reconstruction planning. Work is ongoing to determine why some foundations are stable for hundreds of years while others appear less robust and liable to change and which can help shape reconstruction responses. Although at an early stage of analyses, the considerable age of superstructure timbers inevitable means that they are showing decomposition attributes that influence timber strength. Care should be given in their reuse as main construction timbers notwithstanding the long cultural tradition that they hold.

Geotechnical Assessments

The geotechnical team studied the local subsoil condition at Pashupati, Bhaktapur, Changu Narayan, Jaisidewal and Trailokiya Mohan, utilising the excavation trenches that had previously recorded cultural sequences to the natural soil level. One exploratory borehole to 10 metres depth was drilled at each location to understand the soil stratigraphy at each site and to collect soil samples for laboratory testing with the intention of understanding the local soil types present at these sites (Figure 12). This also allowed the further performing ground response analysis and back analysis viz. numerical modelling to understand the potential causes of destruction during the earthquake and also to develop recommendations for any remediation technique to be adopted to restore the affected structures. Both disturbed and undisturbed samples were collected at various depths from each borehole and transported to Durham for geotechnical testing. A total of 31 disturbed and 18 undisturbed samples were collected from all the boreholes for characterization and evaluation of engineering properties. Preliminary results indicate that the soil present at Pashupati and Changu Narayan may be categorised as site class D (Stiff soil) whereas soils present at Bhaktapur, Trailokiya Mohan and Jaisidewal are under site class D (Soft soil) as per NEHRP (2009) guidelines. The presence of stiff soil lowers the chances of any wave amplification during an earthquake event for Pashupati and Changu Narayan, however, other sites might have experienced wave amplification and period elongation.

It is important to note from the particle size distribution curves for all the soil samples collected that all these sites have potential for liquefaction under certain level of earthquake as per the limits specified by Tsuchida and Hayashi (1971). The plasticity chart given by Seed et al. (2003) also confirms the potential of soil liquefaction at these sites, though evidence of liquefaction was not observed during site visits. This may be due to the absence of groundwater at shallow depth during the 2015 Earthquake. This was the beginning of the

summer season in Kathmandu and ground water abstraction may have been responsible for artificially lowering water levels.

Structural Assessments

Symmetrical geometric configuration is the main feature of ancient structures surveyed in Kathmandu (Figure 13). Brick masonry walls act as a load-bearing system in these structures and wall thickness varies between walls on different stories. Inclined timber struts transfer the roof loads from tiled roofs to the masonry walls. In terms of seismic standpoint, masonry monuments and buildings are brittle structures in which mortar joints acts as plane of weakness. Experience has shown that masonry buildings are one of the most vulnerable of the entire building stock under strong earthquake shaking (Sarhosis et al. 2016). The large number of human fatalities in such constructions during past earthquakes corroborates this. Ground vibrations during earthquakes cause inertia forces at locations of mass in the building. These forces travel through the roof and walls to the foundations. The main emphasis is on ensuring that these forces reach the ground without causing major damage or collapse.

During our post-earthquake reconnaissance surveys conducted in 2017, minor to serious levels of damage were identified in most of the structures surveyed. It is important to note that several of these structures had already survived the great 1934 Nepal-Bihar Earthquake ($M_w=8.1$), the 1988 Udaypur Earthquake ($M_w=6.9$) and the 2011 Sikkim-Nepal Earthquake ($M_w=6.9$). Most of this has been attributed to age related deterioration of construction materials and also the lack of regular maintenance, however, the rehabilitated strength of these temples is yet to be established. Diagonal and vertical line cracks near the corners of the masonry walls, cracks in the crown portion of the temples and out-of-plane collapse of

masonry walls were the main damage mechanism observed during the follow up survey conducted in 2018. 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 at Pashupati. It was also noted that the heritage structures were more affected as compared to modern reinforced concrete structures. Minor damage was observed at Changu Narayan, however, the Kasthamandap experienced partial to complete collapse. Figure 14 illustrates the out-of-plane collapse of an unreinforced masonry wall of a courtyard building located south-west of the Pashupati temple complex. This may be mainly 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. Inspection within the building revealed vertical cracks in many masonry wall panels. A wide crack of 80 millimetres was observed at third floor level in one of the masonry walls due to the complete collapse of a portion of the wall (Figure 15). Such level of cracking is difficult to repair and requires rebuilding of the part of the wall.

Stone built temples at Pashupati did not exhibit such large crack patterns as it is evident from Figure 16, where a stone built temple was observed to be intact as compared to a temple constructed of brick masonry located less than 30 metres away (Figure 17). 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.. 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. The possibility of rotation and differential settlements in the foundation components of these structures were also explored during the reconnaissance survey. At present,

restoration works are ongoing in many structures with an aim to rebuild and preserve their ancient architecture but this is still challenging.

In summary, the primary cause of damage in these structures appeared to be associated with insufficient structural resistance, rather than foundation failure and this structural inadequacy has been exacerbated by a lack of regular maintenance, inadequate bending and shear stiffness of the masonry walls. The response of these structures did not depend only on the structural system but also on soils and foundation parameters, location and type of structures and the nature of earthquake. To safeguard these structures from future earthquakes, it is suggested that periodic inspection and maintenance of existing archaeological infrastructure, together with a program of more detailed structural assessment has the potential to increase the seismic resilience of these structures; however, it is also necessary to implement maintenance programmes that are consistent with the historical importance of these structures. Data acquisition techniques could be effectively used to record damage at a large scale on a regular basis (Dhonju et al. 2017 and 2018). In such a scenario, individual effort is not sufficient to survey all of the heritage structures in an emergency situation. Community or citizen participation, consisting of heritage digitisation and documentation, could potentially contribute significantly to heritage preservation. Advances in digitisation and documentation of heritage structures could be coupled with advanced numerical modelling strategies can significantly reduce the cost of structural inspection and assessment (Kassotakis et al. 2018). In addition, a study is planned to understand the combined response of soil and heritage structure under the prescribed 2015 earthquake acceleration-time history and obtained geotechnical investigation data by using finite element based commercial software PLAXIS2D. This study will provide an insight regarding the static and seismic response of the heritage structure which may help in planning for the strengthening measures need to be adopted for partially damaged monument structure.

Visualisation

AHRC's Curious Travellers project (www.visualisingheritage.org) is a data-mining and crowd sourced infrastructure which is helping to record, manage and interpret archaeological sites, monuments and heritage at risk. It provides a priority response to the globally important challenge of sites that have been destroyed or are under immediate threat from natural disasters, neglect, conflict and cultural vandalism. The project uses two workflows to scrape web-based imagery and crowd-source imagery to recreate 3D models of sites and monuments at risk. Many threats to heritage are linked to issues of access – impacting conservation and site management as well as the safety of individuals. Its approach is to offer sustainable solutions working with extant imagery that does not place individuals at additional safety risk, whilst helping to contextualise visible archaeology by linking to relevant site and landscape data and integrating this into local historic environment record frameworks that make this data freely accessible to all. As threats to heritage ensue largely without an agreed framework of response or mitigation, the potential of safeguarding by record demonstrates the importance and timeliness of digital documentation methods.

One of the valuable consequences of UNESCO World Heritage Site status is that countries can benefit from the visibility of these sites through increased tourism with associated socio-economic gains. While UNESCO promote the universal value of world heritage sites, such sites often become emblematic to a country and are linked to cultural identity and commodification (Graham et al. 2016). It is because of this widespread familiarity, that sites achieve global recognition – a status that has been abused in fragile contexts because of the potential visibility and notoriety achieved through destructive acts that harm these sites and communities connected to them (Frey and Steiner 2011), serving as a form of propaganda

(Gonzalez-Zaradona et al. 2017) and in separating terrorist recruits from societal and cultural norms. Significantly, the visibility of heritage sites also offers the potential to harness digital imagery as a force for good. The development of mobile technologies and in particular the widespread adoption of high resolution camera phones and geospatially-referenced imagery, offer opportunities for 3D digital documentation. Such methods combine geospatial imaging practice and computer algorithms that have developed alongside conventional photogrammetry practice for use with archaeology and heritage applications. When used with complementary tools, such as imagery from satellite and UAVs, the potential of imagery for heritage protection and new interpretations is fully realised. Where cultural heritage sites have been threatened, or destroyed, it is widely accepted that these new digital recording methods must be one response to the situation of heritage at risk. Furthermore, digital terrain models and photogrammetry are important tools in evaluating damage and structural stability.

The Curious Travellers project was initiated in the wake of iconoclastic acts in Islamic State-controlled territory within the Middle East, and earthquake destruction in the Kathmandu Valley (Wilson 2016; Faber et al. 2017). A key part of the project has been to use confirmatory measures to assess the accuracy and efficacy of using diverse image datasets to derive 3D data. The ethics of conservation serve to guide our workflow – in striving for authentic representation using high fidelity 3D models built from rich image data. These approaches do not alter, or remodel digital content without clear indication and discussion of the case and merit for such changes. In essence, the workflow follows the same conservation ethos that helped to coalesce support for the protection of architectural heritage in the UK around ventures such as the Weald & Downland Open Air Museum at Singleton – a reaction to the destruction of vernacular architecture as townscapes were transformed in the 1960s and 1970s. Instead of the logistically complex process of physically dismantling heritage structures and rebuilding them elsewhere, the practice continues using transformative digital

methods that include structure-from-motion photogrammetry and 3D laser scanning. This approach complements other responses that relate to multi-scalar efforts with artefact reconstruction, large scale landscape recording, together with geospatial inventories for heritage assets.

Through our efforts, we recognise that the safeguarding of local participants is of critical importance and that crowd sourcing and voluntary participation for development, whilst useful are not suited to every application. For these reasons we have used openly-available web-scraped imagery supplemented by donated imagery to derive high resolution 3D digital models. From web-scrapes of images, nearly one million images have been downloaded. Approximately 70,000 of these images have now been sampled and filtered out to be looked at for selected monuments in Kathmandu, of which 25,000 individual images were matched into clusters of images. Three of largest clusters cover Hanuman Dhoka's Durbar Square, Bhaktapur's Durbar Square and the temple complex at Pashupati. Point clouds for the Durbar Squares and temples are around 350 million points in total, where possible these have been processed to produce meshed and textured models. Our downloaded images, database files and processed data adds up to around 2.8TB of data and we are already able to present historic urban cityscapes which no longer exist (Figures 18 and 19).

Community Engagement and Dissemination

Integral to our approach, community engagement began in December 2017 with a scoping visit with the initial objectives of talking with people and communities associated with site visits about the level of consultation, discussion and engagement they have with reconstruction agencies. This was followed in April 2018 by a survey based on a structured questionnaire conducted with local residents and communities within Hanuman Dhoka's

Durbar Square, and in the areas around the Kasthamandap and Jaisidewal, sites at which archaeological, geotechnical and architectural evaluations had been, and was, being undertaken. At the time, despite the appointment of Community Mobilisers by the Department of Archaeology (Government of Nepal), some heritage managers were still hesitant to engage with local residents as they feared that it would complicate their work, lengthen the reconstruction process and take up too much of their time. One stated ‘we can't take into account everyone's views and opinions. They are missing the point! Unfortunately recent experience with 'activists' protesting against restoration work has reinforced a negative impression of 'community' engagement’. Partly in response, our own survey was conducted by a collaborative team from Durham University, Tribhuvan University and the Department of Archaeology (Government of Nepal) and included students from Tribhuvan who received training and practical experience in conducting community surveys and interviews (Figure 20). The main objectives of the survey were to understand the role of immediate community in the continued use and management of the monuments and the squares around; asking their opinion on the rebuilding of these monuments and what their role has been so far; and capturing their personal stories and how they have been able to recover or not in the last three years. A total of 322 people were interviewed and while the analysis of the survey results is still on-going, we have begun to identify specific characteristics of the monuments, including maintenance and organisation, new local stories regarding the monuments, and practices before and after the earthquakes.

With reference to maintenance activities and local involvement, preliminary analysis indicates that very few people nearby are involved in the *guthis* or religious institutions that traditionally managed the Kasthamandap and Jaisidewal. However, there seemed to be slightly more local involvement at Jaisidewal, where a priest who used to perform rituals at the temple was interviewed and where the Jaisidewal Youth Club was mentioned as being

active in the temple, including cleaning and maintenance activities. Surveyors also recorded local stories that residents had about the temples. One of these stories, told by several people, remembered that one of the timbers inside the Kasthamandap was associated with healing power. People with pain used to scratch the affected parts of their body against the timber and, it was told, the pain would go away. The survey also indicated changes in the ritual practices before and after the earthquakes. While many of the festivals associated with this area have recovered and continue to take place annually, some local festivals and daily rituals at the Kasthamandap have stopped since the protective fences have been put up. A particular event that people have mentioned does not take place anymore is Bhai Tika, when a woman known as the Universal Sister used to give *tika* or blessing to men who did not have a sister present to perform the ritual at home during Dashain festival celebrations.

With respect to the reconstruction processes and on-going activities at these monuments since the earthquakes, our survey indicated that most residents had little information regarding the future restoration plans for the Kasthamandap and Jaisidewal. Respondents recognised that because they were busy in their day-to-day life they could not make efforts to get information on the research linked to the monument and learn about the on-going reconstruction process. While a majority of respondents were affirmative that they would continue to visit the monuments after their reconstruction, one of the interviewees indicated how the limited communication and local participation risks undermining other deep local spiritual connections with the temples and other heritage monuments: ‘because we don't feel part of all this work and nobody tells us anything or asks our advice, I have less interest in looking after the place. It doesn't seem like ours. So I'm not going to stop people or tell them off for using it to dry their clothes or sell things from it. Just an information board would be a start. Some people did talk with us but nothing happened. Why are you different?’.

After this interview, the heritage site manager prepared and established an information board at Jaisidewal. The survey points to the need to ensure that local residents are given access to information about outcomes of research and plans for the future reconstruction of temples and monuments. This requires far greater transparency from reconstruction teams and government departments. Ultimately, most respondents envisioned that at the end of the reconstruction there would be an inaugural ritual, like a Chhema Puja. The example of the rituals at the Kasthamandap described in our Introduction indicate how effective dissemination of archaeological investigations results can materially contribute to the continuity and change of these rituals and be re-used by local communities to enrich and re-establish their local spiritual, social and historical connections with the monuments.

The results of our survey are being shared with the Municipality and representatives of the Government of Nepal. At the same time as the information was shared, the interdisciplinary team were invited to participate in the development of a new museum experience in Hanuman Dhoka, an earthquake museum, by the Director-General of Archaeology Mr Bhesh Narayan Dahal, and the Head of the Hanuman Dhoka Palace Museum Development Committee, Madam Aruna Nakarmi. This led to the development of a collaborative exhibition developed by Durham University's UNESCO Chair in Archaeological Ethics and Practice in Cultural Heritage, Durham's Oriental Museum, the Department of Archaeology (Government of Nepal), ICOMOS (Nepal), UNESCO, and the University of Stirling. The exhibition, titled 'Resilience within the Rubble', highlights the challenges faced during the process of rebuilding World Heritage Sites in post-disaster situations and the tensions raised by the obligation to ensure that the heritage that survived the earthquake is not itself irreversibly damaged. Focusing on the experience of the team's post-earthquake rescue research across Kathmandu, it explores the contribution that interdisciplinary research can make to understanding why individual monuments fell and how they can be rehabilitated

with greater resilience but without triggering a second cultural disaster. Installed in the historic Dhukuti building within the UNESCO World Heritage Monument Zone at Hanuman Dhoka, it was formally inaugurated on the third anniversary of the Earthquake by Her Excellency Bidhya Devi Bhandari, the President of Nepal, with the Federal Minister of Culture, the late Rabindra Prasad Adhikari (Figure 21). The bilingual exhibition was designed to highlight the threats to Kathmandu's historic infrastructure but also celebrated many of its vernacular skills and presented the ambitions of the British Academy GCRF Cities and Infrastructure project. Between 25th April and 20th November 2018, the exhibition gallery was visited by 27,691 Nepalis, each of whom paid 30 rupees each to visit; 17,602 from South Asia, who paid 150 rupees each to visit Hanuman Dhoka and the Dhukuti Museum; and 103,866 international visitors, who paid 1,000 rupees each to visit Hanuman Dhoka and the Dhukuti Museum.

Prospect

At the start of our project we had prepared a statement for ODA compliance that started by recognising that Nepal was an LDC in long-term post-conflict and post-disaster recovery and thus eligible for ODA funding. We also recognised that our proposal had a relevance to Nepal's development challenges as the United Nations Development Programme had stated that reducing disaster risk is essential to achieve SDGs (<http://www.undp.org/content/undp/en/home/climate-and-disaster-resilience.html>) in alignment with the Sendai Framework observation that 'It is urgent and critical to anticipate, plan for and reduce disaster risk in order to more effectively protect persons, communities and countries, their livelihoods, health, cultural heritage, socioeconomic assets and ecosystems, and thus strengthen their resilience' (2015:10). As such, we stated that our

project would directly reduce risk to life and livelihoods by protecting development gains associated with SDG 11, as well as strengthening progress through partnerships (SDG17). Furthermore, we argued that by preserving Kathmandu's authenticity and intangible traditions through the co-production and dissemination of a methodology to evaluate the seismic safety of historic urban infrastructure, we would directly address challenges of 'resilience and action on short-term environmental shocks' and 'sustainable cities and communities'. Within the scope of our two year and £299,992 funded project, we believe that we have met many of those ambitions, some planned and some unplanned.

In line with our original work plan, members of the interdisciplinary team joined together to participate in a Kathmandu-based dissemination workshop at the end of the project towards the end of 2019. Hosted by the newly reopened National Museum in Kathmandu and its Director, Mr Jai Ram Shrestha, the event was held across two days and involved leading experts and professionals from a range of disciplines, including archaeology, conservation, architecture, heritage management, planning, and economics from Nepal, France, India, Austria and the UK along with local stakeholders to discuss contemporary issues and solutions for the protection of heritage in the face of seismic shocks. The first day was launched by two keynote expert lectures from Professor P.N. Maskey and Professor S.R. Tiwari, both from Tribhuvan University's Institute of Engineering, and followed by technical presentations from the interdisciplinary speakers. The first day was attended by 92 delegates and was followed by a second day focused on 63 engineering, heritage, culture and archaeology masters and research students enrolled in four Kathmandu based institutions. The first interdisciplinary education event of its kind to be organised in Kathmandu, feedback (on a scale of 1-5 with 1 being low) was positive with sampled students acknowledging that their participation had enhanced their understanding of integrated engineering, archaeology and heritage practices (3.68); that it had also provided them with an opportunity to wide

range of activities beyond their usual study (3.89); and, finally, that their training had been enhanced through their participation in the workshop (3.42). Both engineering and archaeology students also recorded it as the first joint programme that they had attended with students from other disciplines.

We also participated in additional, initially unanticipated, international dissemination activities. These included team presentations in Vienna in October 2018 following a formal invitation from the Austrian Academy of Sciences to co-design and contribute to their International symposium on the protection and preservation of Nepal's cultural heritage 'After The Earthquake: Research, Protection and Preservation of Nepal's Cultural Heritage'. This was accompanied by a public keynote lecture on the British Academy project by Robin Coningham at the Academy, whose audience included the Nepali Ambassador to Austria as well as the Director-General of Austria's National Commission for UNESCO, as well as radio interviews and an article on ORF's (Austrian Broadcasting Corporation) online 'Science' section. Our team have also participated in the British Council and FAPEG-funded Researcher Link Workshop on 'Geohazard Risk Reduction in Unplanned Urban Areas' at Caldas Novas, Brazil in September 2018. Additionally, a photograph of the puja at the end of the rescue interventions at the Kasthamandap was featured as a frontispiece in the international journal *Antiquity* on the eve of the third anniversary of the Gorkha Earthquake (Figure 22).

The co-production and installation of our earthquake exhibition within the Kathmandu Valley's UNESCO World Heritage Site certainly contributes also to our original ambitions although initially unplanned. We have also seen the direct transfer of research from the field to the discussions of the Kasthamandap Reconstruction Committee, in the words of its Chair, Mr Rajesh Shakya:

‘This helped to scientifically resolve the ever existing debate about the date of construction of the Kasthamandap and the history of the Kasthamandap was pushed further back in time. Furthermore the investigation also indicated the probable reasons behind the collapse of the Kasthamandap. It was clear that the lack of timely maintenance as well as improper interventions in the past was instrumental in the collapse of the Kasthamandap. The Kasthamandap is but a tip of the iceberg. There are numerous monuments and sites in Nepal awaiting for proper archaeological studies that could uncover great information about their past. In absence of strong heritage policy in Nepal, the heritage structures are continuously being encroached erroneously – sometimes by national agencies and sometimes by neighbouring elements. We are witnessing erratic heritage rebuilding practice prevailing right around the Kasthamandap – Trailokiya Mohan Temple and Maju Dega to name a few. The Kasthamandap has proved the importance of archaeological and scientific study, especially for those cases where history and culture are embedded inside the surface’.

His comments confirm that, whilst successful, our interdisciplinary partnership also demonstrates that gaps still remain and our pilot now needs to be scaled up. It is also clear that a quite different task connected the seismic performance of monuments refitted with modern material still awaits, particularly as evidence of the performance of such hybrids is being steadily removed during the reconstruction process despite their unknown seismic performance.

We also recognise the challenges that we have encountered during our field and research programme with respect to the accessibility of data, which is spread amongst agencies and individuals. For example, there is no central archive for borehole data across the Kathmandu’s Valley’s World Heritage Monument Zones and no agreed format for their analysis and reports within Kathmandu. Many significant early photographs of key sites and monuments are still in private hands and remain largely inaccessible and undigitised, despite

the risk from earthquake. Additionally, inscribed materials from sites are stored by the National Archives while objects are housed by the National Museum and records and architectural drawings by the Department of Archaeology. That said, not all monuments within the World Heritage Site have still not been recorded and many of the original elevations and plans of historic monuments also remain in private hands. Reflecting on the Kathmandu Valley's rich corpus of early Licchavi inscriptions (Vajracarya 1993; Mirnig 2016), it is also notable that this invaluable and irreplaceable dataset remains at risk from future seismic activity as well as rapid urban development. Again, digitisation through the collection of 3D scans of individual inscriptions would offer preservation through record although a database linked to location and current state of conservation and threat is needed extremely urgently. The creation of such a database would also facilitate future monitoring. In parallel, although our work has focused on monuments within Kathmandu's World Heritage Monument Zones, there is an even greater threat to historic urban infrastructure beyond the core and buffer zones, including the extremely vulnerable urban core of Kathmandu's first city, Harigaon. In this light, there is a very clear need for effective data infrastructure to both identify gaps as well as to process, preserve, protect and make available data within appropriate applications to support continuing research, maintenance and management. This will need to involve the application of a complex mix of technologies, including but not restricted to hardware, software, servers, networks and cloud services, together with the appropriate governances and access process and policies. It is anticipated that a combination of Geographical Information Systems (GIS) linked to Building Information Modelling (BIM) can contribute to achieving these aims. Digital models can store physical representations of structures and sub-surface conditions. It could also be used to store contemporary and historic images of the individual monuments, allowing the creation of the 4D dimension, time. Of particular interest will be the best way to store intangible

information as attributes of the physical model. Naturally, this is dependent upon the provision of ongoing financial, staff resource and host but should be prioritised as the physical risk to physical copies from future seismic activity is clear. Ideally, the data needs to be accessible via a single access route but this would also require the development and implementation of a primary data store in the form of a relational database. Once this is established a read-only replica of the data store can be developed and made available in order to allow access to the data without compromising its security. We must also continue to bridge the gap between modern architectural and engineering approaches to Kathmandu's vernacular architecture and the traditional knowledge by the mastercraftsmen and artisans as currently both have very separate reference points although the current reconstruction efforts at the Kasthamandap demonstrates that these are not mutually exclusive. Finally, while we recognise the need for additional geoarchaeological, geotechnical and structural engineering analysis into the performance of Kathmandu's historic infrastructure, we must also be aware that the deployment multi-disciplinary teams must also include community mobilisers and development specialists who can interface between communities, multi-disciplinary teams and other reconstruction experts. Education and preparation is needed for the community, scientists, planners and policy makers, so that communities are at the heart of reconstruction and heritage protection rather than remaining at the periphery. This has important funding and programme design implications but our pilot has demonstrated that community engagement should be given equal status to that of technical protection.

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Note on the Authors

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