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INITIAL GEOLOGICAL AND ENGINEERING ASSESSMENT OF THE 2015 NEPAL, GORKHA M7.8 EARTHQUAKE AND ITS SOCIETAL AFTERMATH

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Abstract

An Mw 7.8 earthquake struck Nepal on April 25, 2015 at 11:56 local time. The shock was felt throughout Nepal and in India, Bangladesh and Tibet. Along with its largest Mw 7.3 aftershock on May 12, it severely affected 14 Nepal districts resulting in 8891 fatalities, 22303 injuries, millions of homeless, earthquake environmental effects (EEE), damage on buildings and infrastructures and great economic losses. Based on field reconnaissance in the affected area immediately after the main shock, primary EEE were not detected, while secondary EEE included slope movements, liquefaction, ground cracks and hydrological anomalies especially in the Kathmandu valley suggesting a combination of directivity and deep basin effects. Masonry and cultural heritage structures suffered most damage due to inadequate construction and poor maintenance. In case of sounder construction, such buildings remained intact. Most of reinforced concrete buildings weathered the earthquake without damage despite of possessing high seismic vulnerability in most cases. The earthquake response of buildings was discontinuously nonlinear. It was observed that either partial or total collapse or no horizontal motion, no cracks, no breaking of glass window panels occurred. This fact is a key characteristic of the local domination of vertical excitation and the respective response of structures.

Keywords: Himalaya; Nepal; Kathmandu Basin; Building Damage; Earthquake Environmental Effects

1. Introduction

The Himalayan range foreland basins are among the fastest growing in the last decades and most dense areas in the world. Nepal located in the central Himalaya (Fig. 1) is the 11th most earthquake-prone country and the fastest urbanizing country in the world according to the United Nations Development Programme (UNDP) in 2009. Kathmandu valley constitutes the cultural, economic and political capital of the country and presents a highly dynamic spatial pattern of urbanization, while Kathmandu city ranks first among the most earthquake-prone cities of the world. Ever since the first recorded earthquake of 1255 that killed the one-third of the local population of Kathmandu valley and its King Abhaya Malla, Nepal and Kathmandu valley have experienced a major earthquake every 75-80 years. The last great earthquake in Nepal was the 1934 Nepal-Bihar Mw 8.1 event resulted in more than 10000 fatalities in Kathmandu valley and damage to about 60% of the valley buildings [1]. Similarly, a large Mw 7.8 earthquake struck Nepal on April 25, 2015 and along with its largest aftershock of Mw 7.3 on May 12 caused numerous fatalities and significant effects on the natural environment and the social, productive, infrastructure and cross-cutting sectors.

The main shock is a typical Himalayan-type low-angle thrusting earthquake with very wide slipping area and consequently widespread damage on the natural and built environment of the affected area. Seismic history shows that this event occurred in a seismic gap on a major shear zone marking the underthrusting of the Indian Plate beneath Asia, the Main Himalayan Thrust (MHT) fault in Central Nepal, where no large magnitude earthquakes have been recorded over the past 300 years [2].

This study is structured as follows. An overview upon the geomorphological, geological and neotectonic setting of the wider studied and the affected areas is given in the second section. The seismicity of the Nepal Himalaya is described in the third section, while the seismological data of the Nepal seismic sequence of spring 2015 is found in the fourth section. The EEE and building damage induced by the 2015 Nepal, Gorkha earthquake are presented in the fifth and the sixth section respectively, while the societal aftermath is discussed in the seventh section. Finally, a brief summary of lessons learnt is found in the conclusions section. It is significant to note that the study team moved to Nepal immediately after the main shock and had an unprecedented opportunity to study the actual effects of a large Himalayan earthquake over a car accessible region extending from 60 km northwest to 40 km southeast of Kathmandu city.

2. Geography, Geology and Neotectonics of Nepal

The almost 2500-km-long and from 250 to 400 km wide Himalayan fold-and-thrust belt occupies about 600000 km^2 of area. It is positioned between 75° and 95° east longitude, and 27° and 35° north latitude. The Himalaya was largely formed by the Indo-Eurasian collision over the past 70-50 Ma [3]. It constitutes a part of the greater Himalayan-Alpine system extending from the Mediterranean Sea in the west to the Sumatra arc of Indonesia in the east over a distance of more than 7000 km. This belt was developed by the closure of the Tethys Ocean between two great land masses since the Paleozoic: Laurasia in the north and Gondwana in the south [4]. The Himalayan orogen incorporated all three elements, that is, the Tethys sediments, Indian shield, and Gondwana.

After the collision along the Indus-Tsangpo suture zone, the tectonic activity was partially transferred southwards. The subsequent major event was the formation of the Main Central Thrust, a deep intracrustal fracture in the Himalaya. The next large event occurred still farther south, where the frontal faults developed respectively in the Lesser Himalaya and Siwaliks (Fig. 1). They represent a shallower intracrustal feature. The Himalaya displays a relay of orogenic activity from the deeper inner belt to the shallower outer belt. Thus, the Himalayan orogen has evolved from intense continental deformation, leading to extensive crustal shortening and thickening, large-scale thrusting and folding, polyphase metamorphism and granite intrusion along with exhumation, uplift, and erosion episodes.

Nepal (Fig. 1) is located in the central part of the Himalayan arc and extends between 80°04′ and 88°12′ east longitude, and 26°22′ and 30°27′ north latitude. The country approximates an oblong and occupies an area of 147181 km^2. Its maximum length is about 825 km, and its width varies between 250 and 170 km from west to east, respectively. About 80 % of Nepal's land is occupied by mountains. Its altitude ranges from 64 m in the plains of southeast Nepal to 8848 m at Mount Everest, both within an aerial distance of about 150 km, where the climate quickly changes from subtropical to arctic conditions.

In Nepal, the structural setting is defined by three northerly dipping major thrusts, which are the Main Frontal Thrust (MFT), the Main Boundary Thust (MBT) and the Main Central Thrust (MCT) from south to north respectively (Fig. 1). These three major thrust faults in the Nepal Himalaya sole at depth into the Main Himalayan Thrust (MHT), which marks the underthrusting of the Indian Plate [5, 6]. Moreover, they clearly separate the major tectonostratigraphic units of Nepal Himalaya, which are the MFT hanging wall (Sub-Himalayan or Siwalik Zone), MBT hanging wall (Lesser Himalayan Zone), MCT hanging wall (Higher Himalayan Zone) and STD hanging wall (Tibetan – Tethyan Himalayan Zone) (Fig. 1). More specifically, the MFT separates the Quaternary alluvium of the Indo-Gangetic depression from the Siwalik Group comprising Neogene fine- to coarse-grained continental strata (~20 - 2 Ma). The MBT separates the Siwalik Group from the weakly metamorphosed rocks of the Lesser Himalayan Sequence comprising low-grade Proterozoic metasedimentary and metavolcanic strata, augen gneiss (1870-800 Ma). The MCT places high-grade metamorphic rocks (800-480 Ma) of the Greater Himalayan Zone comprising kyanite-sillimanite, gneiss, schist and quartzite over the low-grade metamorphic rocks of the Lesser Himalayan Sequence [6] (Fig. 1). It has been recognized that metamorphic grade increases up-structural section towards the north from the Lesser Himalaya to the Greater Himalaya [7]. The MCT is the oldest of these gently north-dipping thrusts followed by the MBT and the MFT respectively.

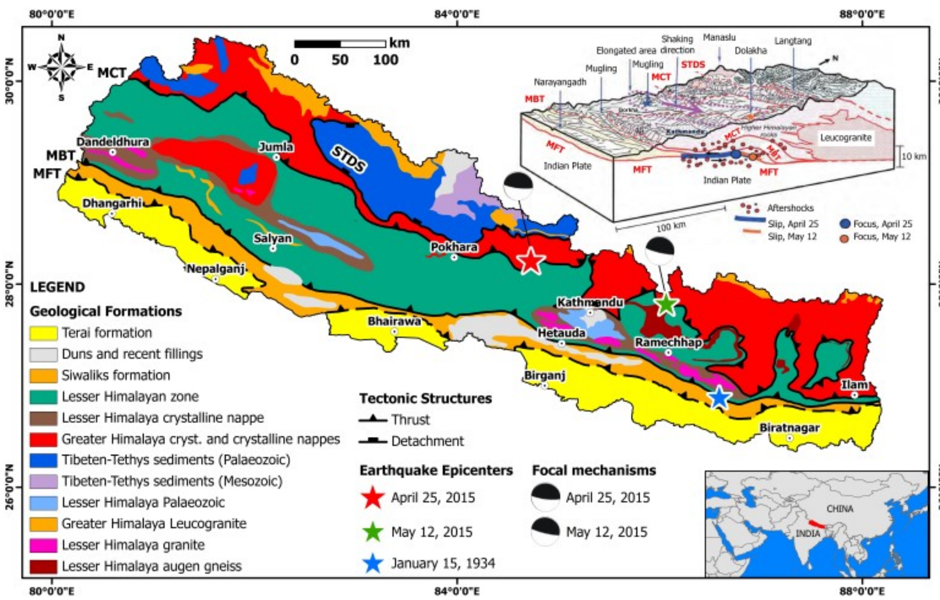

Fig. 1 – Geological map of Nepal after [8] with the epicenters of the April 25, 2015 Nepal, Gorkha earthquake and its largest aftershock and a block diagram after [9] illustrating the approximate locations of slip during the April 25 and May 12, 2015 ruptures and the aftershocks. The elongated area suffered severe damage.

As far as neotectonics is concerned, the prominent active faults systems from W to E along the Nepal Himalaya are the NW-SE striking dextral strike-slip Karakoram Fault, the generally NW-SE striking Main Central Active Fault System comprising strike-slip and northerly dipping faults, the generally NW-SE striking Main Boundary Active Fault System including northerly and southerly dipping faults and the generally NW-SE striking Himalayan Frontal Fault composed of strike-slip and northerly and southerly dipping faults [10]. Among these, active faults along the MBT and MFT are the most active and have potential to produce large earthquakes in the future [11].

The Kathmandu basin is an intermontane basin lying on the Kathmandu Nappe located in the Lesser Himalayan zone [6] (Fig. 1). It is filled with young semi-consolidated fluvio-lacustrine sediments of Pliocene to

Quaternary age comprising muds, silts, sandy loams, sands and conglomerates. Their thickness varies from place to place with its maximum estimated as 650 m based on gravity measurements. The basement rock in Kathmandu valley consists of Bhimphedi and Phulchoki Groups of the Kathmandu Complex and was reached through drillhole at a depth of 550 m at the central part of Kathmandu City. The Bhimphedi Group is an approximately 8 km thick metamorphic succession composed of schists, quartzites, marbles, and allied rocks together with Sheopuri injection gneisses and Paleozoic granites and the Phulchoki Group is 5-6 km thick and comprises mainly limestones with Neoproterozoic or Early Cambrian – Devonian shales and sandstones [5].

The sedimentation of Kathmandu basin is strictly related to and controlled by the interaction of active tectonics and fluvial processes in the surrounding area. The Chandragiri Fault and the Chobhar Fault running through the Late Pleistocene colluvial slopes and terraces on the southern part of the basin and the Kalphu Khola Fault running through the Late Pleistocene gneissic boulder beds on the northwestern part of the basin are the most significant tectonic structures controlling the basin sedimentation [12] along with the fluvial processes of the Bagmati River and its tributaries.

3. Seismicity of the Nepal Himalaya

Accurately located epicenters in the Central Nepal region define a 50-km-wide narrow zone located between the MBT and the MCT, while their majority of them are located close to the MCT [13]. Seismic events with well-determined focal depths define a simple planar zone extending from 10 to 20 km depth and north-dipping about 15° [13] (Fig. 2a). The majority of the available focal mechanisms of seismic events within this region indicate a dominant thrust environment with the existence of shallow north-dipping thrusts [13]. The aforementioned data argue that the MFT, MBT and MCT sole at depth into the MHT (Fig. 2a), which is the interface between the Indian shield and the Himalayan sedimentary wedge (Fig. 2a) and the main geological structure for the accumulation of elastic strain along this boundary. The shallow southern flat of this structure is locked during the interseismic period (Fig. 2a) and acts as an asperity in the seismogenic zone that could generate great earthquakes, while the deeper northern parts of the MHT are believed to be creeping smoothly. The transition zone between the locked and creeping segments is believed to accommodate interseismic elastic strain. The accumulated elastic stress along this transition zone is gradually released through intense microseismic activity (Fig. 2a) and moderate seismic events that cluster along foothills of the Higher Himalaya [14]. Large and great events are generally generated along the locked portion of the MHT and the ruptures propagate toward the Indian plain along the MHT [15] (Fig. 2a). Some of these ruptures reach the surface either at the front forming fault scarps or fault-related folds or along out-of-sequence thrusts [16, 17]. This is not the rule since some ruptures do not reach the surface as in the case of the 1905 Kangra and the 1991 Uttarkashi events.

The earthquake catalogue for Himalaya goes back to the first century, and at least from the 16th century it seems to be complete for large earthquakes [18]. Based on historical and instrumentally recorded earthquake data, it is concluded that the Kathmandu valley has been struck by moderate ($5.0 \leq M < 7.0$), major or large ($7.0 \leq M < 8.0$) and great ($M \geq 8.0$) seismic events with high intensities. Earthquakes in Central Himalayan with significant damage to Kathmandu valley are reported since the 13th century in historical records and recent studies and specifically in 1100 (Mw ~8.8, intensity $>X_{MMI}$), 1255 (July 6, Mw ≥8.1, intensity $>X_{MMI}$), 1408 (September 14, Mw ≥ 8.4-9.2, intensity $>X_{MMI}$), 1505 (June 6, Mw 8.1, intensity $\geq VII_{MMI}$), 1803 (September 1, Mw 7.5-8.0, intensity $>IV_{MMI}$), 1833 (August 26, Mw 7.6, intensity X_{MMI}), 1905 (April 4, Ms 7.8±0.05, intensity X_{MMI}), 1934 (January 15, Mw 8.1, intensity $>X_{MMI}$), 1991 (May 23, Mw 7.0, intensity III_{MMI}) and 2011 (September 18, Mw 6.9, intensity V_{MMI}) [19].

4. The 2015 Nepal, Gorkha earthquake

The Nepal, Gorkha earthquake occurred on April 25, 2015 at 11:56 local time and was assessed as 7.8 (USGS, GFZ, IPGP) or 7.9 (HARV). It caused intense ground shaking throughout Nepal and parts of India, Bangladesh and Tibet. The main shock and its largest aftershocks severely affected districts of Central Nepal resulting in 8891 fatalities, 22303 injuries, millions of homeless, many EEE, damage on buildings and infrastructures as well as great economic losses in the order of 10 billion U.S. dollars. Nearly 8 million people were affected by the earthquake sequence.

Its epicenter was located near the Barpak Village of Gorkha district which is 81 km northwest of Kathmandu and its focal depth was approximately 10-15 km. All focal mechanisms provided by seismological institutes and observatories (Fig. 1, 2b) indicated a low-angle fault plane with NW-SE strike parallel to the Himalayan Belt and dip to NE at 7°-12°. The aftershock sequence within the first 45 days after the main shock included about 3000 events recorded by the permanent network of the National Seismological Centre (NSC) in Kathmandu with most hypocentral depths in the range between 2 and 25 km [20]. The aftershocks occurred in a narrow zone with width of about 40 km, along the southern slope of the high Himalayan range [20] (Fig. 2b). This spatial distribution is consistent with the focal mechanisms provided for the main shock. The aftershocks in the western part of this distribution were concentrated close to a topographic high, while in the eastern part two clusters were defined: a large cluster observed immediately after the main event in Kathmandu area and coincided with the main ruptured fault segment and a smaller one located at the eastern end of the seismic cluster that occurred after the largest Mw 7.3 aftershock of May 12 [20] (Fig. 2b) and coincided with a deeper rupture to the east. The first aftershocks occurred in an area located in a distance of 120 km east of the main shock epicenter. More than 120 aftershocks with magnitude ML > 4.0 followed the main shock in the first 12 hours. The number of aftershocks was decreased until the generation of the Mw 7.3 largest aftershock on May 12 with epicenter in Sunkhani of Dolkha district located 76 km northeast of Kathmandu (Fig. 2b) and similar focal mechanism with the main shock (Fig. 2b). This aftershock was located in the easternmost part of the aftershocks distribution and followed by a large number of aftershocks, 70 of which had magnitude ML > 4.0 [20].

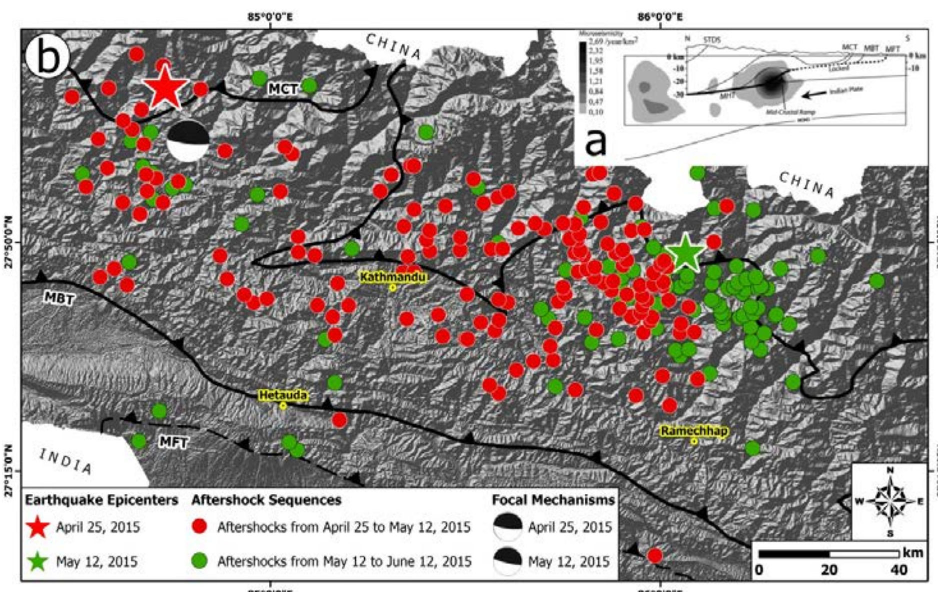

Fig. 2 – (a) Generalized N-S cross section through the Central Himalaya. The southern flat along the MHT is locked during the inter-seismic period resulting in elastic stress accumulation, which is released through microseismicity in Nepal Himalaya. The great earthquakes are generally originated along the northern flat just front of the Higher Himalaya [6]. (b) The epicenters, the aftershock sequences and the focal mechanisms of the main shock on April 25, 2015 and of its largest aftershock on May 12, 2015 respectively based on [21].

Initial finite fault models show slip ranging from 2 to 4 meters at a depth of about 15 km over a zone extending about 150 km ESE of hypocenter [22]. Based on [23, 24], no surface rupture occurred from this earthquake or any of the subsequent aftershocks. However, a highly disrupted zone in Araniko Highway could be attributed to thrust faulting directly located under the Kathmandu basin. As far as the recorded ground motion is concerned, the maximum horizontal peak ground acceleration (PGA) of the earthquake recorded at the KATNP [21] strong motion station in central Kathmandu was 0.164g with a vertical component of 0.186g, maximum velocity of 0.86 cm/s and maximum displacement of 139 cm. This PGA is very low despite of the large earthquake magnitude and the small epicentral distance of central Kathmandu. Based on interferometric data and the derived surface deformation measurements, it is concluded that no major discontinuities in phase near the surface trace of the MHT are detected [22]. Most of the displacement from the May 12 aftershock was observed close to the eastern tip of the displacement induced by the April 25 main shock indicating that stress interaction is the most possible explanation for the occurrence mode of these earthquakes in the Nepal Himalaya [25]. The main shock produced changes in the state of stress of sufficient magnitude to trigger the largest aftershock on May 12.

5. Earthquake Environmental Effects

Based on [23, 24, 26], primary effects directly linked to the surface expression of the seismogenic source were not detected in the field after the 2015 Nepal, Gorkha earthquake. Palaeoseismological studies suggest that the 1255 and 1934 earthquakes (Mw $\geq$ 8.1) ruptured the surface along the MFT south of Kathmandu [27], while field observations and related studies after the 2015 main shock suggest that the rupture extended only to the base of the MFT [23, 24, 26]. However, as mentioned above, a wide ground deformation zone in Araniko Highway could be attributed to thrust faulting directly located under the Kathmandu basin (Fig. 3a, b, c)

The 2015 Nepal, Gorkha earthquake and its aftershocks induced slope movements with adverse effects on the local population, buildings and infrastructure including burial and destruction of several villages, hundreds of fatalities, partial or total destruction of roads and natural damming of rivers posing significant hazard due to landslide dam burst and consequent catastrophic downstream flooding. Almost 6000 of landslides were triggered by the earthquake sequence and were distributed over an area of approximately 35000 km^2 in Nepal [28]. Few extremely large-volume (>250000 m^3) landslides were triggered despite the magnitudes of the April 25 and May 12 events and the rugged morphology of the affected area. The observed slope movements were classified as rock falls, rock slides, soil falls and soil slides (Fig. 3a, b). The majority of them occurred in areas comprising fractured, weathered and thus unstable geological material susceptible to failure along steep slopes. They were observed not only close to the epicenter of the main shock, but also in the eastern part of the seismic sequence due to the eastward-directed fault rupture of the main shock and the generation of the largest aftershock Mw 7.3 on May 12 in the same area. Almost 70 valley-blocking landslides were reported in the affected region with volume ranging from 500 to 2000000 m^3, while half of the dams were empty due to either dry rivers or dam breaching [28]. The observed lake surface areas ranged from 50 to 35000 m^2 and averaged 1700 m^2 [28]. Nearly all of them were breached within one month following the earthquake.

Liquefaction induced by the 2015 Nepal, Gorkha earthquake appears to be limited and localized in susceptible to liquefaction areas along the fringes and within Kathmandu valley and was sparser than usually expected from an earthquake of such magnitude. The generation of this earthquake sequence in the middle of the dry season, when the moisture level in the soil was quite low, might have contributed to lower instances of soil liquefaction. These phenomena were induced particularly in Ramkot, Manamaiju, Guheshwori, Lokanthali, Bungamati, Changu Narayan, Mulpani, Gwarko/Imadol, Hattiban, Kamalvinayak, Bhaktapur, Syuchatar, Jharuwarashi and Nepal Engineering College areas [26, 29, this study]. Moreover, liquefaction in the form of silt boils and lateral spreading occurred due to the earthquake inside Trishuli dam reservoir located northwest of Kathmandu valley. The main liquefaction manifestation in the affected area included (i) sand boils ejecting sandy material resulting in flooding of the surrounding area (Fig. 3c) during and after the main shock in April 25 and the large aftershocks followed in the first hours and (ii) ground fissures associated with lateral spreading in gentle slopes and in short distance from rivers within the Kathmandu valley. The soil profile of the liquefaction-affected areas comprises silty clay or silt on the top followed by low-plasticity silty clay locally known as black cotton clay 0.5-1.5 thick and loose fine sand up to 3 m depth. These deposits coincide with shallow water table up to 1.3 to 3 m below ground surface. Liquefaction phenomena caused severe damage mainly to masonry buildings in Kamalvinayak, Bhaktapur and Syuchatar areas, while few of the reinforced concrete buildings experienced damage where liquefaction occurred under the building foundation.

Ground cracks in the affected area are considered as EEE induced by the ground shaking during the main shock and its largest aftershocks. They were mainly developed in liquefied areas due to liquefaction-induced lateral spreading and in geotechnical unstable areas due to the generation of earthquake-induced slope movements. A characteristic example of cracks was observed along a segment of the Kathmandu-Bhaktapur Road section of the Araniko Highway in the Lokanthali area (Fig. 3d, e, f). Cracks with 2 m deep fissures and vertical offset up to 1.5 m were observed over a large area with gentle slope to a river channel and caused ground fissuring and subsidence, slope failures and sinking of the main and access roads, damage to reinforced and gravity retaining walls, settlement and tilting of buildings and damage to footbridges. Based on various field reports [23, 24, 26], these structures were associated with lateral spreading. However, taking into account the observed structures such as monoclinal escarpment, tension cracks and small-amplitude folds and the fact that these cracks are in agreement with preliminary models of co-seismic slip suggesting that the largest amount of slip on the fault was located just below the Kathmandu city, this highly deformed zone could be attributed to thrust faulting.

Elevated groundwater levels and substantially increased spring and streamflow volumes were reported in the watersheds all along the MBT for many weeks following the main shock [24].

Fig. 3 – Typical EEE induced by the 2015 Nepal, Gorkha earthquake: (a, b) landslides along the road network of the affected area, (c) liquefaction phenomena in Guheshwori from [26] (d, e, f) ground cracks strongly related to liquefaction-induced lateral spreading along a segment of the Kathmandu-Bhaktapur road section of the Araniko Highway in the Lokanthali area.

6. Buildings types of the affected area and damage to buildings and infrastructures

The dominant building types in the affected area are the following: (a) Reinforced concrete (RC) buildings. They are frequently constructed in urban city areas with RC column and beam frames (RC frames), concrete floors and roofs, and unreinforced infill walls of solid clay bricks with cement mortar. The reinforcement comprises four deformed longitudinal bars in columns and beams, with widely spaced ties. They are classified in low- (1-3 storeys), medium- (4-6 storeys) and high-rise (> 6 storeys) buildings. (b) Unreinforced buildings with masonry load-bearing walls. They have rectangular shape in plan and 1-4 storeys. Their foundation comprises bricks or stones. Different types of masonry were observed including solid bricks, concrete blocks, adobe and stones with cement, lime or mud mortar as well as mixed types. The masonry walls are often exposed without external or internal plasters. Wooden or masonry lintels are used to span over openings such as doors and windows. Wooden frames support heavy mud floors and roof of various types such as roof slabs, sloped wooden-framed roofs, canopies with corrugated galvanized iron and clay or stone tile finishes. The construction types vary based on location (urban, semi-urban and rural) and construction age (old and recent). (c) Wooden frame buildings. They comprise post and beam frame up to 3 storeys, timber floors and roofs made of galvanized iron sheets. The infill walls are composed of wooden planks or galvanized iron sheets or bamboo with mud plaster on either side. (d) Old cultural heritage structures. They are classified as buildings with traditional brick masonry and timber frame structures, brick masonry structures in lime or mud mortar and buildings made from stones. Three styles of architectural design are observed in the affected area: Tiered/Pagoda, Chaitya/Stupa and Shikhara style. Despite many differences within each style, the main load-bearing system of the traditional temples comprises multi-layered brick walls. The outer layer is made of good quality (fired clay) bricks, the middle layer of brick fragments and mud and the inner layer of poor quality materials (sun dried bricks). (e) Industrial structures including typical steel structures with truss and steel columns and composite steel structures with steel truss and RC columns.

Well-constructed RC buildings sustained no to moderate damage. Poorly built and non-engineered RC buildings suffered minor, moderate and severe damage not only to non-structural but also to structural elements. Non-structural damage included cracks with multiple patterns in infill walls (e.g. diagonal cracks, horizontal cracks at the beam interface and vertical cracks at the column interface), detachment of large pieces of plaster from infill walls, detachment of infill walls from the surrounding RC frame and partial or total collapse of infill walls. Damage to structural elements of low- and mid-rise buildings comprised cracks and fracturing in beam and columns, shear failure or compression crushing of the supporting columns along with the elastic behaviour of beams, tilting (Fig. 4a, b), foundation failure resulting in overturning and partial or total collapse, soft story failure due to absence of infill walls and stirrups at the beam-column joint location, pounding of adjacent buildings resulting in partial collapse or tilting (Fig. 4b,c) as well as pan-cake type collapse due to heavy loads from the upper storeys and insufficient column sizes. Damage to high-rise buildings was observed to non-structural elements and comprised cracks in infill walls and detachment of large pieces of plaster in the lower storeys (first and second) followed by the medium storeys. Damage to RC buildings was due to poor geometric configuration (too long in one direction, extension of masonry wall beyond column line), poor quality of construction materials and concrete with comprehensive strength lower than the expected, non-seismic detailing and absence of earthquake resistant features, lack of implementation of proper ductile detailing of reinforcement even in recent constructions, lack of geotechnical provision and inappropriate foundation on slopes.

Damage to unreinforced masonry buildings include diagonal cracks often originating from the openings in the masonry load-bearing walls (doors and windows), vertical corner cracks along the mortar joints of the brick walls, partial collapse of multi-layered walls, collapse of the upper storeys of the buildings and roofs, while the lower storeys remained intact, out-of-plane failure of roof gable due to its location at the top of the building and to its vibration as a free standing unit, tilting due to foundation failure, damage due to pounding with heavier adjacent buildings and partial or total collapse of the building (Fig. 4e, f, g, h). Damage to unreinforced masonry buildings were due to the placement of construction materials in a random manner, the large thickness of the load-bearing walls along with heavy floors and roofs resulting in heavy structures attracting large inertial forces during large shocks, lack of interlocking connection between main and cross walls, poor connection between the wall and the diaphragm and absence of continuous horizontal bands for developing confining box action of walls.

Major destruction was observed at various square complexes, world heritage sites and many other historical structures of cultural and archaeological significance in Kathmandu valley. The observed damage varied significantly based on the construction age and the structural systems. It mainly comprised residual deformation of the ground floor level of the temple, cracks in masonry walls, partial or total collapse of masonry walls (Fig. 4i, k, l), sway of the timber frame and partial or total collapse of the structure. Damage to old cultural heritage structures were due to old construction age, unusual structural systems, fatigue of monuments from past earthquakes, lack of maintenance and poor quality restoration after the 1934 Nepal-Bihar earthquake.

The industrial structures were slightly or no damaged by the 2015 Nepal, Gorgkha earthquake sequence. The detected damage was limited to infill walls and included their cracking and partial collapse.

The infrastructure sectors in the affected area are (i) electricity, (ii) community infrastructure, (iii) communications, (iv) transport and (v) water, sanitation and hygiene. The electricity generation and supply network was partially damaged. Substations and distribution lines collapsed or were damaged and remained not operational for several weeks resulting in loss of access to electricity for numerous households. Community buildings used for meetings, social events and child care collapsed. Many telecommunications and broadcasting towers were mounted on top of buildings resulting in adverse effects to the stability of the building due to the additional loads. Many towers were out of service due to damage on the installation building, while network congestion and downtime were also experienced. The transport facilities were also suffered damage. The road network throughout the mountainous terrain experienced partial or total destruction due to secondary EEE. Retaining wall failures and few bridges were also damaged. The Sindhupalchowk, Dolakha, and Nuwakot districts were the worst affected. International and domestic airport facilities sustained only minor damage. Critical facilities and systems absolutely necessary for safe aircraft landing and taking off sustained only minor damage and the airports remained operational playing an important role to the seismic disaster management in general and to the short-time emergency response in particular. Water supply and sewerage systems and related buildings suffered moderate to severe damages including partial or total collapse.

7. Societal aftermath

The earthquake casualties could have been much higher considering that the main shock struck on Saturday when schools in Nepal are closed for weekly holiday and in the middle of the day when most of people were in the fields and open public spaces. The loss of life from the 2015 Nepal, Gorkha earthquake and its largest aftershocks was mainly due to poor construction of buildings characterized by insufficiency or absence of reinforcement and earthquake resistant features, irregular building plans, poor quality of construction materials and concrete, lack of geotechnical provision and inappropriate foundation on geotechnical unstable slopes and zones. Secondarily, the generation of secondary EEE in the affected area and especially numerous slope movements resulted in the devastation of residential areas mainly in the mountainous parts of the affected area with rugged morphology. About 600-1000 fatalities were induced by the generation of secondary EEE with more than 100 by the largest aftershock [30].

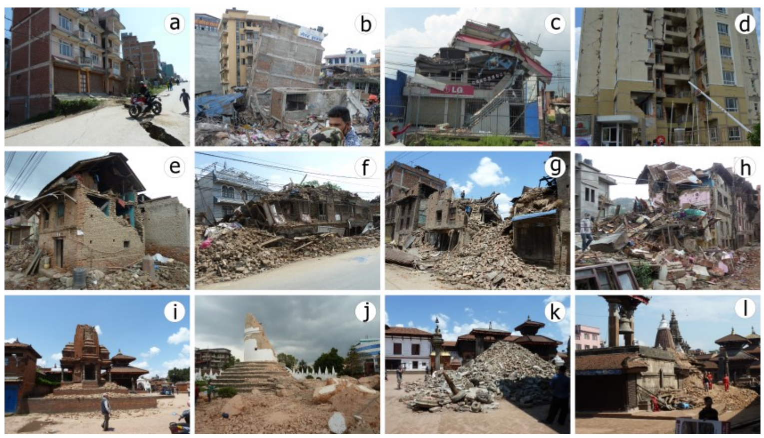

Fig. 4 – The first row illustrates damage on RC buildings: (a) Tilting close to ground cracks strongly related to liquefaction-induced lateral spreading, (b, c) partial and total collapse, (d) moderate damage to non-structural elements of high-rise apartment building. The second row illustrates damage to masonry buildings: (e) partial collapses of the side walls, (f, g) partial collapse and (h) total collapse of masonry buildings close to undamaged RC buildings (f, g, h). The third row illustrates damage to old cultural heritage buildings of various construction types and especially partial (i) and total collapse of temples (j, k, l).

Deterioration of the health conditions was observed and comprised secondary health-related problems along with the immediate medical needs in the most affected area. Diarrheal diseases, skin problems, and other infectious diseases such as cholera showed up in many communities mostly from rural areas where people are living in shelters with poor hygiene and lack of toilet facilities, poor quality drinking water and unhealthy food handling practices [31]. There was also significant amount of trauma where people have been doing manual work for provision of emergency shelters or building restoration [31].

On April 26, 2015, the Government of Nepal declared state of emergency and appealed for international humanitarian assistance [30]. The response phase was characterized by a huge national and international mobilization for providing immediate relief and emergency assistance and included search and rescue operation, first-aid treatment and medical care, mitigation of the impact of the induced phenomena, provision of essential emergency supplies and emergency shelters and post-earthquake building inspection among others. Personnel and means of Nepal Army, Nepal Police, Armed Police Force, civil servants, search and rescue teams as well as medical teams from many different countries and the private sector along with the cooperation of voluntary and non-governmental organizations, local people, civil societies, media and political parties were mobilized immediately and provided significant assistance to the affected people in difficult conditions of chaos, confusion and distress. The traumatic experience and the associated losses of this earthquake sequence will accompany Nepalese people and will have a long-term effect on the economy and development efforts for a prolonged time period. As the earthquakes will forever affect Nepal, there is no choice but to regain stability and orientation and to adapt to natural hazards.

8. Conclusions

The 2015 Nepal, Gorkha earthquake is considered as one of the most destructive earthquakes of Nepal Himalaya since the great 1934 Nepal-Bihar earthquake as it severely affected 13 Nepal districts (Sindhupalchok, Kathmandu, Dolakha, Kabhrepalanchok, Lalitpur, Dhading, Gorkha, Bhaktapur, Nuwakot, Rasuwa, Sindhuli, Kaski, Parbat) (Fig. 5f) in terms of EEE (Fig. 5a), fatalities (Fig. 5b), injuries (Fig. 5c), governmental (Fig. 5d) and public building damage (Fig. 5e). The other districts were slightly or moderately affected. Because Nepal had not experienced earthquakes of this magnitude for more than 80 years, people and state authorities were less prepared for such an incident.

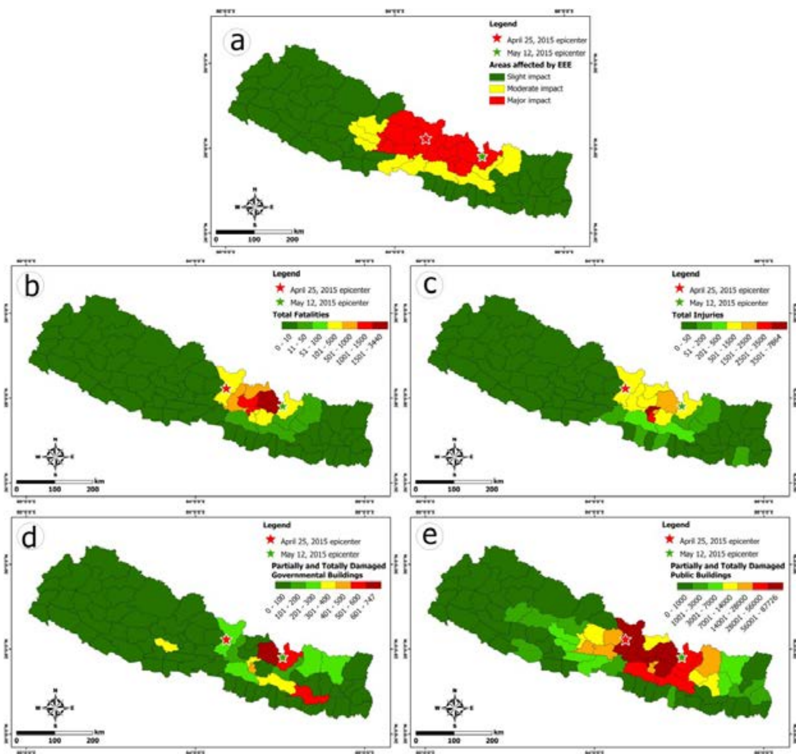

Fig. 5 – Distribution of (a) EEE, (b) fatalities, (c) injuries, (d) damaged governmental buildings and (e) damaged public buildings induced by the 2015 Nepal, Gorkha earthquake and its largest aftershocks to the Nepal districts based on governmental reports [30] last updated on June 05, 2015.

EEE included ground cracks are associated with thrust faulting in Kathmandu city and with liquefaction-induced lateral spreading in Kathmandu valley, slope movements in the hilly and mountainous areas in the Lesser, Greater and Tethyan-Tibetan Himalayan Zones, liquefaction phenomena and hydrological anomalies especially in Kathmandu valley suggesting a combination of directivity and deep basin effects. The observed EEE increased losses and damage in Kathmandu valley due to the amplification of long-period ground motion and in several mountainous villages which were devastated by landslides.

The well-designed RC buildings show good performance sustaining minor reparable damage in structural elements but severe damage to non-structural elements. Poor construction of non-engineered RC buildings resulted in their collapse. The majority of masonry constructions lack proper seismic design and consequently they sustained heavy damage. The dominant type of the observed damage included corner cracks, diagonal cracks, multi-layered wall collapse, gable failure and partial or total collapse. Old cultural heritage structures suffered varying levels of damage based on construction age and structural system. Industrial buildings sustained minor to moderate damage limited to non-structural elements. Infrastructure sectors suffered minor damage except from electricity generation and distribution networks and communication systems.

Taking into account the numerous fatalities, the injuries, the extensive effects on the natural environment, buildings and infrastructures and the societal aftermath of the seismic sequence of spring 2015, it is concluded that the 2015 Nepal, Gorkha earthquake is the most destructive generated in Central Himalaya since the 1934 Nepal-Bihal earthquake with a long-term effect on different aspects of the life of Nepalese people. The most significant lesson Nepal learnt from this earthquake is that the best way to mitigate the disastrous earthquake effects is the restoration of the existing structures to better standards, the construction of earthquake resistant structures and the increase of preparedness at all levels of administration.

9. References

[1] Pandey MR, Molnar P (1988): The distribution of intensity of the Bihar-Nepal earthquake 15 January 1934 and bounds of the extent of the rupture zone. *Journal of Nepal Geological Society*, **5**, 22-44.

[2] Ader T, et al. (2012): Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: implications for seismic hazard. *Journal of Geophysical Research*, **117**, B04403, doi:10.1029/2011JB009071.

[3] Rowley DB (1996): Age of initiation of collision between India and Asia: A review of the stratigraphic data. *Earth and Planetary Science Letters*, **145**, 1-13.

[4] Şengör AMC, Natal'in BA (1996): Palaeotectonics of Asia: Fragments of A Synthesis. In: Yin A, Harrison M (eds) The Tectonic Evolution of Asia, Rubey Colloquium, Cambridge University Press, Cambridge, pp. 486-640.

[5] Dhital MR (2015): *Geology of the Nepal Himalaya. Regional Perspective of the Classic Collided Orogen. Regional Geology Reviews*, Springer.

[6] Chamlagain D, Gautam D (2015): Seismic hazard in the Himalayan intermontane basins: an example from Kathmandu Valley, Nepal. In: Shaw R, Nibanupudi HK (eds) Mountain hazards and disaster risk reduction. Springer, Japan, pp. 73-103.

[7] Searle MP, Law RD, Godin L, Larson KP, Streule MJ, Cottle JM, Jessup MJ (2008): Defining the Himalayan Main Central Thrust in Nepal. *Journal of the Geological Society*, London, **165**, 523-534.

[8] Upreti BN, Le Fort P (1999): Lesser Himalayan Crystalline nappes of Nepal: problems of their origin, *Geological Society of America Special Paper*, **328**, 225-238.

[9] Dahal RK (2015): Engineering Geological Issues after Gorkha Earthquake 2015 in Nepal - a preliminary understanding. *10th Asian Regional Conference of IAEG*, Kyoto, Japan.

[10] Nakata T, Kumahara Y (2002): Active faulting across the Himalaya and its significance in the collision tectonics. *Active Fault Research*, **22**, 7-16.

[11] Chamlagain D, Kumahara Y, Nakata T, Upreti BN (2000): Active faults of Nepal Himalaya with references to Himalayan frontal fault and their neotectonic significance. *QUCTEHR*, Kumaon University, Nanital, India.

[12] Nakata T (1984): Tectonic landforms of several active faults in the Nepal Himalayas. *Journal of Nepal Geological Society*, **4** (special issue), 67-80.

[13] Ni J, Barazangi M (1984): Seismotectonics of the Himalayan collision zone: geometry of the underthrusting Indian plate beneath the Himalaya. *Journal of Geophysical Research*, **89**, 1147-1163.

[14] Pandey MR,Tandukar RP, Avouac JP, Lavé J, Massot JP (1995): Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). *Geophysical Research Letters*, **22** (7), 751-754.

[15] Avouac JP, Bollinger L, Lavé J, Cattin R, Flouzat M (2001): Le cycle sismique en Himalaya. *Comptes Rendus de l'Académie des Sciences*, **333**, 513-529.

[16] Mugnier JL, Huyghe P, Gajurel AP, Becel D (2005): Frontal and piggy-back seismic ruptures in the external thrust belt of western Nepal. *Journal of Asian Earth Sciences*, **25**, 707-717.

[17] Kumar S,Wesnousky S, Jayangondaperumal R, Nakata T, Kumahara Y, Singh V (2010): Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: timing, size, and spatial extent of great earthquakes. *Journal of Geophysical Research*, **115**, B12422. http://dx.doi.org/10.1029/2009JB006789 (20 pp.).

[18] Kayal J R (2008): Large and great earthquakes in stable continental region of India: a review. *Journal of the Geological Society of India*, **68**, 31-46.

[19] Mugnier J-L, Gajurel A, Huyghe P, Jayangondaperumal R, Jouanne F, Upreti B. (2013): Structural interpretation of the great earthquakes of the last millennium in the central Himalaya. *Earth-Science Reviews*, **127**, 30-47.

[20] Adhikari LB, Gautam UP, Koirala BP, Bhattarai M, Kandel T, Gupta RM, Timsina C, Maharjan N, Maharjan K, Dahal T, Hoste-Colomer R, Cano Y, Dandine M, Guilhem A, Merrer S, Roudil P, Bollinger L (2015): The aftershock sequence of the 2015 April 25 Gorkha–Nepal earthquake. *Geophysical Journal International*, **203**, 2119-2124.

[21] USGS United States Geological Survey (2015): M7.8 - 34 km ESE of Lamjung, Nepal. http://earthquake.usgs.gov/earthquakes/eventpage/us20002926

[22] Lindsey E, Natsuaki R, Xu X, Shimada M, Hashimoto H, Melgar D, Sandwell D (2015): Line of sight deformation from ALOS-2 interferometry: Mw 7.8 Gorkha earthquake and Mw 7.3 aftershock, *Geophysical Research Letters*, **42**, 6655–6661, doi:10.1002/2015GL065385.

[23] Angster S, Fielding E, Wesnousky S, Pierce I, Chamlagain D, Gautam D, Upreti BN, Kumahara Y, Nakata T (2015): Field Reconnaissance after the 25 April 2015 M 7.8 Gorkha earthquake. *Seismological Research Letters*, **86** (6), doi: 10.1785/0220150135.

[24] Moss RES, Thompson EM, Kieffer DS, Tiwari B, Hashash YMA, Acharya I, Adhikari BR, Asimaki D, Clahan KB, Collins BD, Dahal S, Jibson RW, Khadka D, Machdonald A, Madugo CL, Mason HB, Pehlivan M, Rayamajhi D, Upreti S (2015): Geotechnical Effects of the 2015 AMgnitude 7.8 Gorkah, Nepal, Earthquake and Aftershocks. *Seismological Research Letters*, **86** (6), 1514-1523.

[25] Galetzka J, Melgar D, Genrich JF, Geng J, Owen S, Lindsey EO, Xu X, Bock Y, Avouac J-P, Adhikari LB, Upreti BN, Pratt-Sitaula B, Bhattarai TN, Sitaula BP, Moore A, Hudnut KW, Szeliga W, Normandeau J, Fend M, Flouzat M, Bollinger L, Shrestha P, Koirala B, Gautam U, Bhatterai M, Gupta R, Kandel T, Timsina C, Sapkota SN, Rajaure S, Maharjan N. (2015): Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal. *Science*, **349** (6252), 1091-1095. doi:10.1126/science.aac6383

[26] Geotechnical Extreme Event Reconnaissance Association (2015): Geotechnical Field Reconnaissance: Gorkha (Nepal) Earthquake of April 25 2015 and Related Shaking Sequence. *Report*, GEER-040, version 1.1. http://www.geerassociation.org/administrator/components/com_geer_reports/geerfiles/Nepal_GEER_Report_V1_15.pdf

[27] Sapkota SN, Bollinger L, Klinger Y, Tapponnier P, Gaudemer Y, Tiwari D (2013): Primary surface ruptures of the great Himalayan earthquakes in 1934 and 1255. *Nature Geoscience*, **6**, 71-76.

[28] Collins BD, Jibson RW (2015): Assessment of existing and potential landslide hazards resulting from the April 25, 2015 Gorkha, Nepal earthquake sequence (ver. 1.1, August 2015). *U.S. Geological Survey Open-File Report*, 2015-1142, 50p, http://dx.doi.org/10.3133/ofr20151142

[29] Okamura M, Bhandarya N, Moria S, Marasinia N, Hazarikab H. (2015): Report on a reconnaissance survey of damage in Kathmandu caused by the 2015 Gorkha Nepal earthquake. *Soils and Foundations*, **55** (5), 1015-1029.

[30] Government of Nepal, Ministry of Home Affairs (2015): Nepal Disaster Report 2015, http://www.drrportal.gov.np/uploads/document/329.pdf

[31] Pandey P (2015): Letter from Nepal, August 12, 2015 - Cholera in post-earthquake Kathmandu. *Travel Medicine and Infectious Disease*, **13**, 425.