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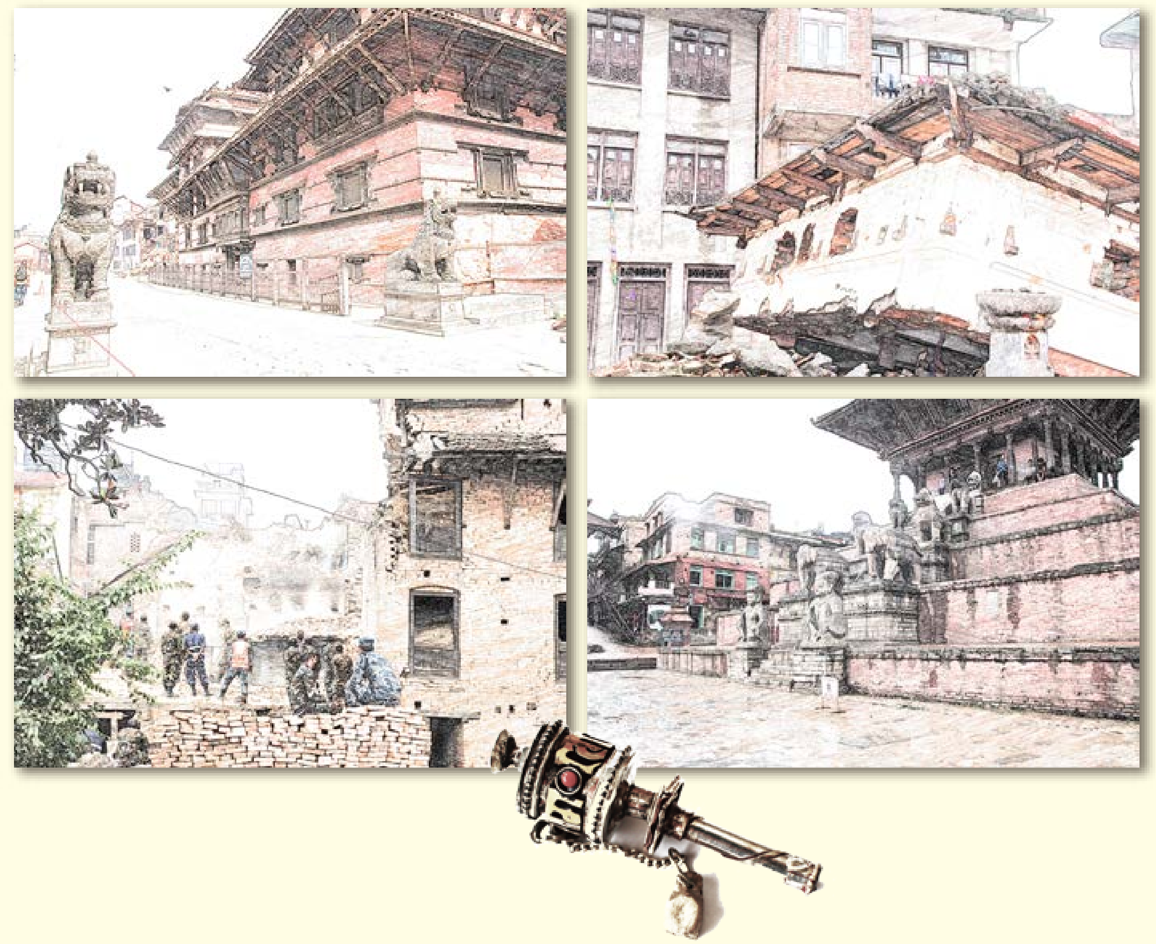
2015年４月ネパール地震（Gorkha地震）における地震の概要と建物被害に関する情報収集調査報告

Investigation of Damage in and Around Kathmandu Valley Related to the 2015 Gorkha, Nepal Earthquake



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防災科学技術研究所研究資料

表紙写真 ‥‥ Damage of historical structures and the houses have been demolished with the support of the Nepal police related to the 2015 Gorkha, Nepal Earthquake.

防災科学技術研究所研究資料

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Technical Note of the National Research Institute for Earth Science and Disaster Prevention: No. 404; March, 2016

Investigation of Damage in and Around Kathmandu Valley Related to the 2015 Gorkha, Nepal Earthquake

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Abstract

An earthquake with a magnitude of 7.8 (M_w) occurred at 11:56 NST (local time) on 25 April 2015, in the central part of Nepal (Gorkha). The National Research Institute for Earth Science and Disaster Prevention (NIED) organized a damage survey team and dispatched it to the affected area for several periods following the earthquake (May 26 to June 3: first trip, June 17 to 24: second trip, August 16 to 21: third trip and October 27 to November 2: forth trip) to investigate the damage and collect data.

In Chapter 1, the first and second surveys were to collect timely statistical information on the damage to brick and stone masonry buildings and to confirm the availability of data and their sources for subsequent surveys. We also carried out a first-hand building damage survey in selected areas. The investigation of the strong-motion data set from the USGS Center for Engineering Strong Motion Data includes information from stations in Nepal that continued to function throughout the main shock and the several subsequent strong aftershocks of the 2015 earthquake.

In Chapter 2, the third and forth surveys were to collect the every building damage survey in selected areas. The motivation behind the survey was to obtain ground truth data for the calibration and improvement of a wide-area damage estimation system that uses satellite data; the system is currently under development by NIED and the Japan Aerospace Exploration Agency (JAXA). A survey of the degree of damage was conducted for every house in Sankhu and Khokana by the European Macroseismic Scale (EMS) -98.

Key words: Gorkha, Nepal Earthquake, Kathmandu, Masonry, Ground truth

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Chapter 1
First trip and Second trip: Situation of damage in and around Kathmandu Valley related to the 2015 Gorkha Nepal Earthquake

1. Introduction

An earthquake with a magnitude of 7.8 (M_w) occurred at 11:56 NST, (local time) on 25 April 2015, in the central part of Nepal (Gorkha). The epicenter was east-southeast of Lamjung, 77 km south-west of Kathmandu, 28.15 at the north latitude and 84.71 at the east longitude, and the depth was 15 km (USGS). According to the statistics by The Nepal Police on 22 June the number of deaths 8,660 and injured 21,952 for the main shock and deaths 172 and injured 3,470 for the aftershock. It was also reported that more than 5,000,000 buildings and houses were damaged and about half those which of had collapsed. This earthquake was officially named as The 2015 Gorkha Nepal earthquake, since the hypocenter was located in the Gorkha region.

A major aftershock with a moment magnitude of 7.3 (M_w) occurred at 12:51 NST on 12 May 2015. The epicenter was 75 km noth-east of Kathmandu and near the Chinese border, 27.82 at the north latitude and 86.08 at the east longitude, and the depth was 19 km (USGS).

The National Research Institute for Earth Science and Disaster Prevention (NIED) organized a damage survey team and dispatched it to the affected area during 26 May to 3 June and 17 to 24 to investigate the damage and collect data. In Chapter1, the findings of this investigation undertaken by this team on the various aspects of the earthquake disaster in the Kathmandu valley (**Fig. 1**).

At the beginning of this Chapter, the tectonics and the seismicity are briefly introduced, and the characteristics of the recorded earthquake ground motions are discussed from the view point of the fault rupture mechanism. The India plate sub-ducts along the Main Himalayan Thrust beneath the Eurasian plate. The Main Himalayan Thrust is dipping at a low angle towards north. Tectonics of the Himalaya region are expected to most continue to rise more than 1 cm/yr.

There were three kings in the Kathmandu valley. Their palaces were in Kathmandu, Bhaktapur, and Lalitpur / Patan. The difference between the renovation works done at these palaces was significant (Not for the historic structures of the old royal palace). Damage to the Old Sanhku was serious, the brick and cement mortar houses were seriously damaged. These structures did not have reinforced concreate (RC) columns.

A numerous number of huge slope failures which occurred in mountainous areas and buried villages and valleys, which resulted in the loss of many lives. Many houses that were caught in landslides, had limited damage. However, the whole scope of the slope failures is not clear at this present time, because any detailed and total survey in the mountainous area as not been carried out. Thus, the number of causalities will be increase as they are found.

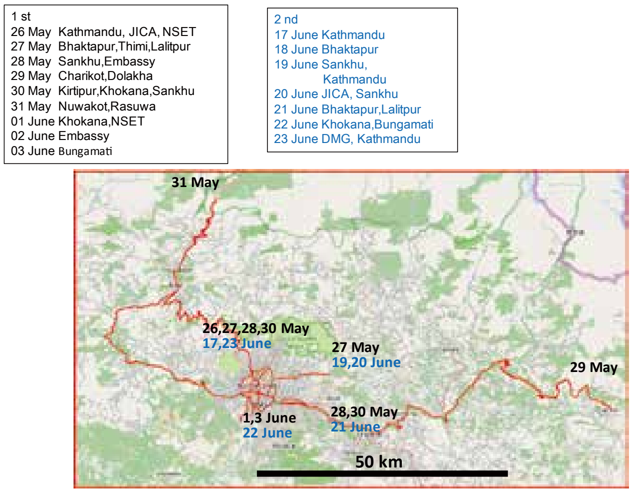

Fig. 1 Survey Route. (OpenStreetMap https://www.openstreetmap.org/)

2. Tectonics of Nepal and Earthquake Ground Motion

2.1 Tectonic Interpretation of the 2015 Gorkha Nepal Earthquake on April 25, 2015

The India plate sub-ducts along the Main Himalayan Thrust beneath the Eurasian plate. Among the most dramatic and visible creations of plate-tectonic forces are the lofty Himalayas, the two large landmasses of India and Eurasia, driven by plate movement to collide. Because both these continental landmasses have about the same rock density, one plate could not be sub-ducted under the other. Thus, the Main Himalayan Thrust is dipping at a low angle 6° - 14° towards north (Mukhopadhyay, 2014) [1]. Tectonics of the Himalaya region are expected to continue to rise more than 1 cm/yr.

2.2 Earthquake Recorded in Kanti Path (KATNP), central Kathmandu

The strong-motion data set from the USGS Center for Engineering Strong Motion Data (CESMD: http://strongmotioncenter.org/cgi-bin/CESMD/iqr1.pl) includes stations from Nepal that continued to function during the main shock and several subsequent strong aftershocks of the 2015 earthquake series.

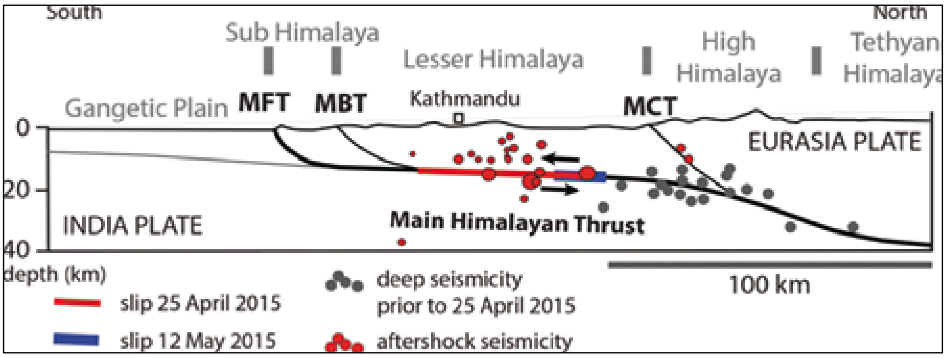

Fig. 2.1 Cross-section of the Main Himalayan Thrust (USGS: The April-May 2015 Nepal Earthquake Sequence)
Generalized cross section showing the approximate locations of slip during the 25 April and 12 May 2015 ruptures on the Main Himalayan Thrust, and approximate aftershock locations of both events.
MFT = Main Frontal Thrust, MBT = Main Boundary Thrust, MCT = Main Central Thrust.
Cross section generalized after Lave and Avouac, 2001 and Kumar *et al.*, 2006.

Fig. 2.2 shows the three components of acceleration and velocity recorded by the CESMD station at the US Embassy in Kathmandu, which recorded the M_w 7.8 main shock (06:11:26 UTC, 28.15°N 84.71°E, 15.0 km deep). **Fig. 2.3** shows the three components of acceleration for the main shock and aftershocks. **Fig. 2.4** shows the three components of velocity recorded for the main shock and aftershocks. Coda waveforms were dominant. **Fig. 2.5** shows the three components of the Fourier spectrum of the main shock and aftershocks. The dominant periods in the Fourier spectra were approximately in the range of 4 to 5 s for magnitude 7 class events. However, for magnitude 5 class events, the dominant periods of the Fourier spectra were about 0.5 s. **Fig. 2.6** shows the three components of the tripartite response spectra of the main shock and aftershocks. The dominant period of the response spectrum was the same as the Fourier spectrum in the period range. The response spectrum of the pseudo velocity exceeds the 400 cm/s level of the response spectra in the case of the main shock.

In **Fig. 2.2**, the vertical velocity motion waveform has two pulse-like ground motions. The main parts of the velocity waveform can be seen centered at two points: 45.08 and 53.07 s. The difference between the rupture start time and arrival time for the S-wave is 8 s. The dominant period of the body wave is about 4 s.

These sizes can be estimated for each strong motion generation area (SMGA) by direct interpretation of body waves.

The methodology shows below;

$$R = T_p \times V_r \qquad (1)$$

$$V_r = 0.72\ V_s \qquad (2)$$

where R: Circular strong motion generation area
T_p: Pulse period
V_r: Rupture velocity
V_s: Share-wave velocity

Thus, two SMGA might existe near the city of Kathmandu.

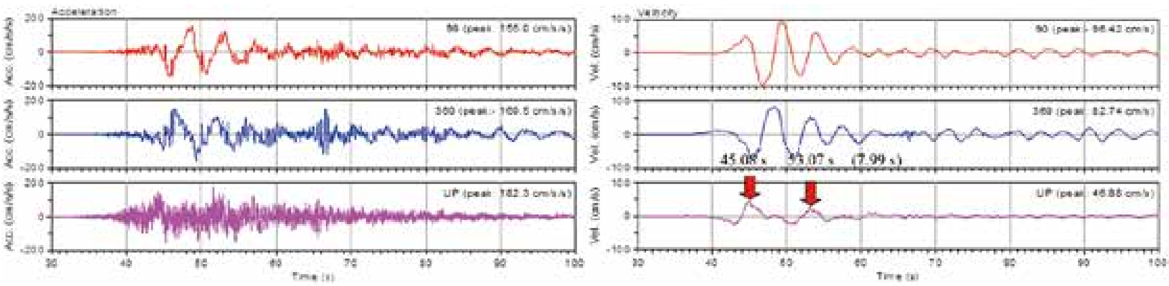

Fig. 2.2 Acceleration (left) and Velocity (light) Record of M_w 7.8 main shock.

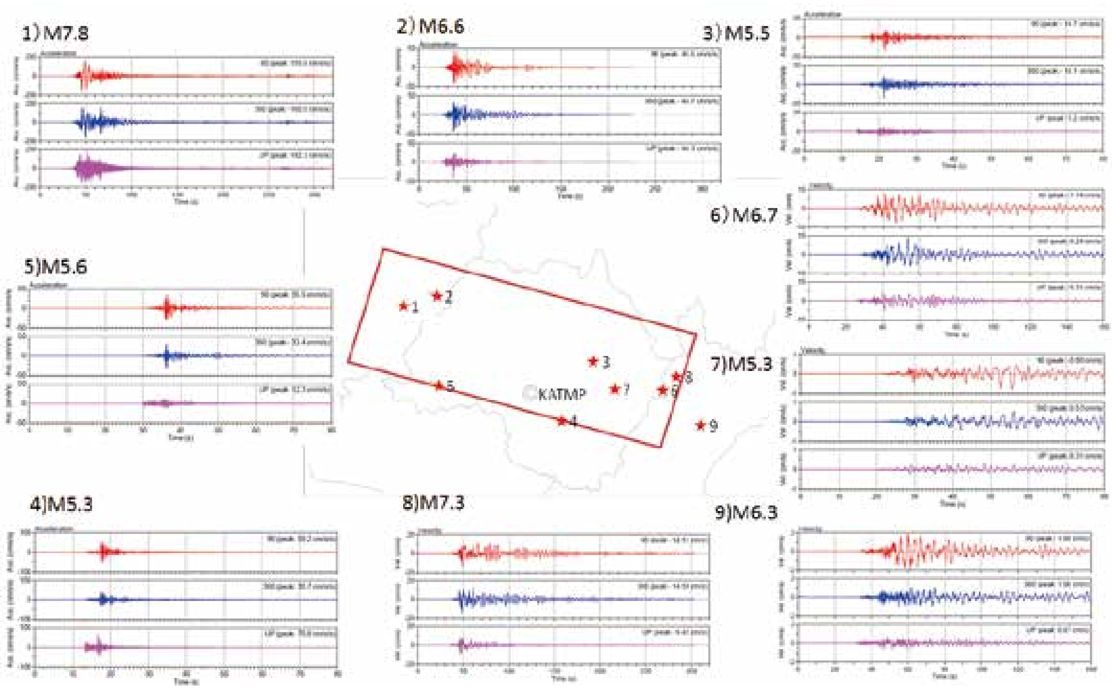

Fig. 2.3 Acceleration Record of Main Shock and Aftershocks.

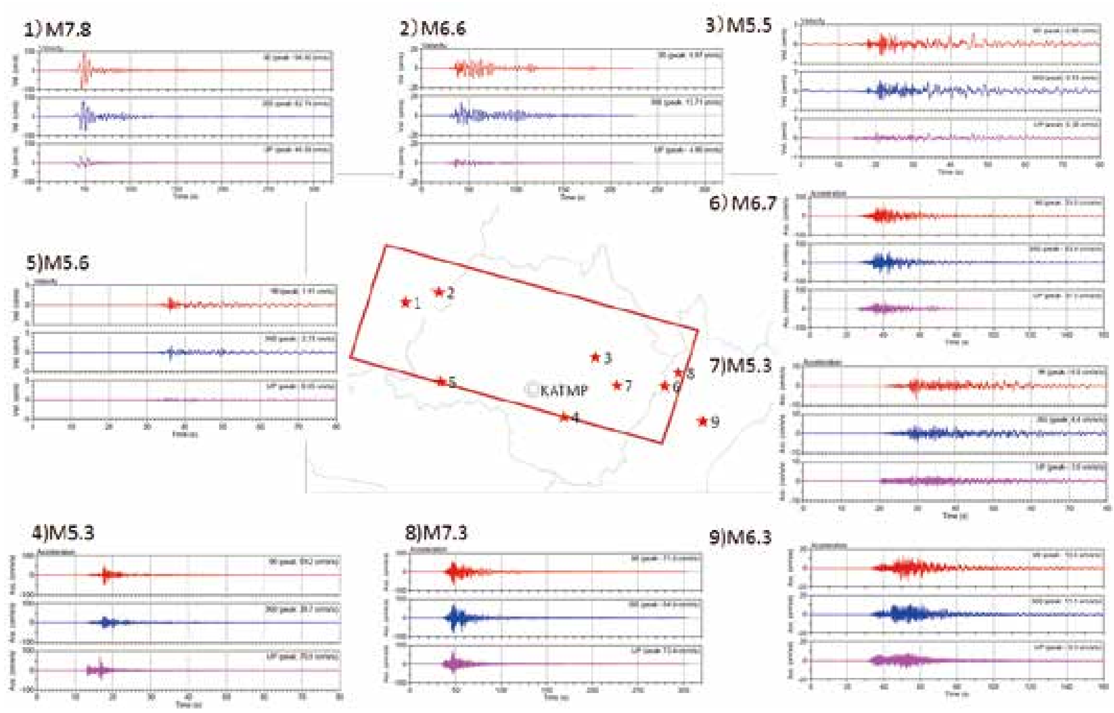

Fig. 2.4 Velocity Record of Main Shock and Aftershocks.

2.3 Risk Assessment Results of JICA 2002

During "The study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002)[2),3),4)]", hazard and damage analyses were conducted. The ultimate purpose of this earthquake disaster analysis was to recognize phenomena associated with a future earthquake in the vicinity of the Kathmandu Valley. Based on the assessment results caused by the scenario earthquakes, a disaster prevention plan can be established. The scenario earthquake fault models are shown in **Fig. 2.7**.

Nepal lies on an active seismic zone ranging from Java –Myanmar – Himalayas – Iran and Turkey, where many large earthquakes have occurred in the past. The historical earthquake catalogue shows the high seismicity along the

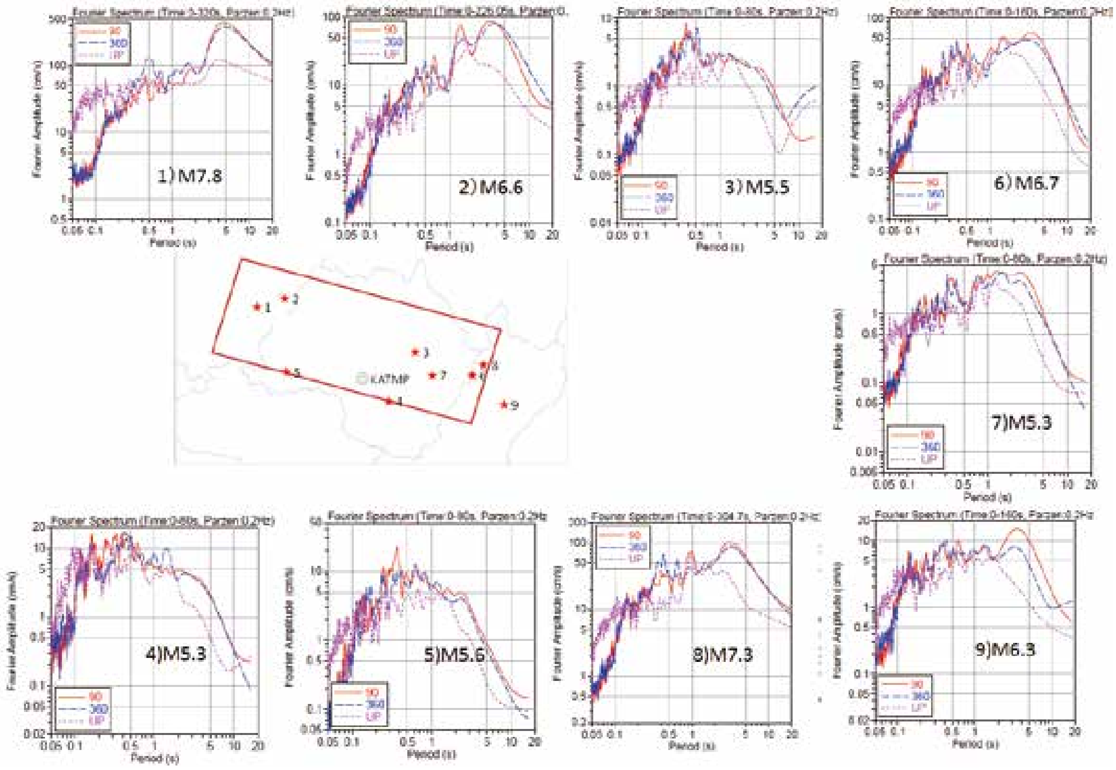

Fig. 2.5 Fourier Spectrum of Main Shock and Aftershocks.

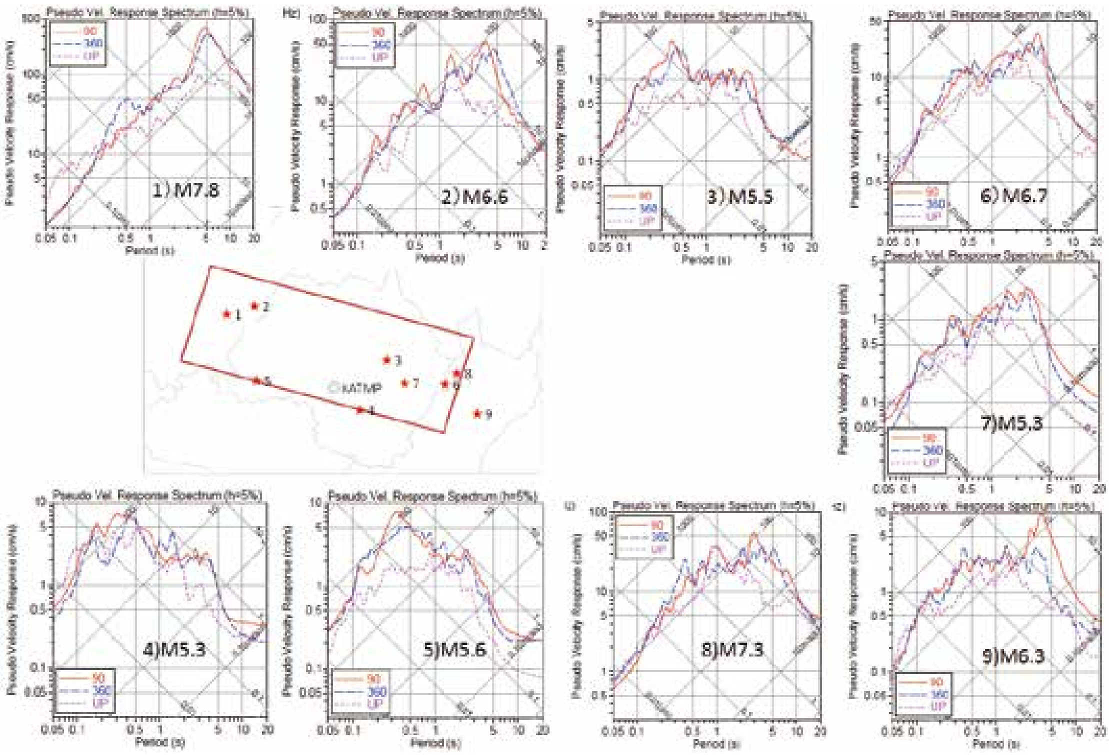

Fig. 2.6 Response Spectrum of main shock and Aftershocks.

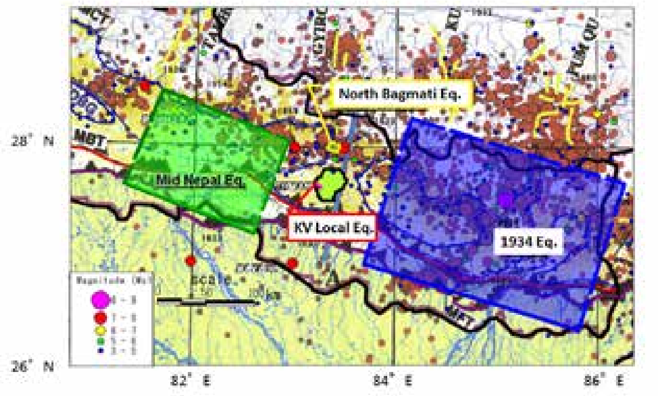

Fig. 2.7 The scenario earthquake fault models (JICA2002).

Himalaya and also the occurrence of huge earthquakes. Kathmandu has suffered damage due to earthquakes several times, including the 1934 Bihar-Nepal earthquake that caused one of the most serious damages to the Kathmandu Valley in the past. Earthquake damage will differ depending on the type and location of the earthquake, such as a huge earthquake outside of the Valley and a small to middle-scale one within the Valley. In the study, four scenario earthquakes have been set, including the 1934 Bihar earthquake recurrence.

1) 1934 Bihar Earthquake (M_w 8.4) Recurrence
2) Mid Nepal Earthquake (M_w 8.0)
3) North Bagmati earthquake (M_w 6.0)
4) Kathmandu Valley local earthquake (M_w 5.7)

The First case is the 1934 Bihar Earthquake (M_w8.4) model, whose fault model is shown as the blue square area. The second case is namely the Mid Nepal Earthquake (M_w8.0), which was the most devastating one which lies west of Kathmandu as the seismic gap area shown in green. The third model is the seismically active with small earthquakes in the near northern part of the Kathmandu Valley which is shown in red. The last model is based on the lineament at base rock in the Kathmandu Valley, as small as magnitude 5.7 (M_w).

2.3 The 1833 and the 2015 Earthquake

The 2015 Gorkha Earthquake is locating be-tween the 1934 Bihar Earthquake and the big Seismic Gap west of Kathmandu or Pokhara. However, according to the historical earthquake information, it is similar to the 1833Earthquake (Oldham, 1833)[5]. The similarity is source area, magnitude class, damaged area and damage features. Even in and around the Kathmandu Valley is the main damaged area, liquefaction is sparse, and building damage was 1,972 (50-60 %), deaths 42 (around 0.2 %). If there exists almost similar typology of buildings in the Katmandu Valley, such as stone and adobe and brick with mud mortar, the current earthquake damage in Kathmandu Valley will be appeared such as building damage 40 %, and fatality will be 0.2 % (National Planning Commission, 2015)[6]. Then there will be similarity between the 1833 and the 2015 Earthquakes. This kind of information will help the future earthquake disaster management in and around the Kathmandu Valley.

3. Damage in Kathmandu Vally

During the Malla dynasties up to 1768, there were three kings in the Kathmandu valley. Their palaces were in Kathmandu, in Bhaktapur, and in Lalitpur/ Patan. The center areas of these palaces are called “*Durbar Square*”.

3.1 Bhakutapur

“*Bhakta*” means Devotee in Sanskrit, and “*pur*” means city. Thus, Bhaktapur is the city of devotees. Bhaktapur’s Durbar Square is a conglomeration of pagodas and Sikhara style temples grouped around a 55 Window Palace of brick and wood (**Fig. 3.1**).

Many of Sikhara in Bhakutapur’s Durbar Square were severely damaged. The steel frame reinforced Chayslin duga temple (left) (**Fig. 3.2**). This temple was no damaged. During the 1934 Earthquake Chyasilin Mandap was completely destroyed. Architects Götz Hagmüller and Niels Gutschow set about rebuilding this temple due to the metal reinforcements by GTZ fund. The Vatsala temple (center), which is Newar style temple, *ca.*1690, but destroyed. Yaksheshvara temple (right) survived.

Harisankara temple

This structure materials are polished decorative bricks of high quality terracotta for lintels of doors and for decorative layers are integrated into the facades (**Fig. 3.3**). Inside materials are unburned bricks and timber frames. This sikhara had to be demolished later.

Chasin Mandapa and Siddhilakshmi Shikhara

Chasin Mandapa (left) was broken in the lintel (**Fig. 3.4**). Siddhilakshmi Shikhara (right) survived, except the top of finial. This temple’s construction used stone and Indian style. This style developed in India during the late 6th century, it only appeared in Nepal during the late Licchavi period, 9th century. There was no damage to the statues of guarding lions and the steps leading to the main entrance. The Fasi Dega was destroyed (**Fig. 3.5**). The large, white Fasi Dega Temple was dedicated to Shiva and it was one of the tallest temples in the second part of Bhaktapur Durbar Square.

Taumadhi Square

Nyatapola Temple, which is a five-storied pagoda, was built by King Bhupatindra Malla in 1702 (**Fig. 3.6**). This is one of the tallest pagoda-style temples in Kathmandu Valley and is famous for its massive structure and subtle workmanship. This temple survived in an earthquake in 1934. This temple remained with a minimum of damage, the reliability of the building technology is being evaluated. The Bhairavnath temple was destroyed by an earthquake in 1934 and subsequently rebuilt.

Dattatreya Square

Dattatreya square in Bhaktapur suffered only one small casualty in terms of collapsed temples. The main Dattatreya temple and others still stand. This temple was originally built in 1427 and is dedicated to Dattatraya, an incarnation of Vishnu.

The God Bishnu festival is held in the Datrataya Temple (**Fig. 3.7**). Usually, this festival is organized every year from July to August. In front of this temple, two statues watchmen / guardians are standing, who provide against evil and disasters. Two watchmen hold Grakata, which is the preferred weapon of Lancers.

The Nepal calendar is currently 2072. Thus, Nepal 1990 B.S. (Bikram Sambat) correspond to 1934A.D. State, this temple collapsed but has not been rebuilt (**Fig. 3.8**). If such non-reconstruction of historical buildings that have been lost during earthquakes does not proceed, it will be a major blow to the future Nepal's tourism-oriented country.

Fig. 3.1 Bhaktapur before / after the earthquake (photo by T. Ohsumi), before / after the 1934 earthquake (Courtesy of MoHA).

Fig. 3.2 Rinforced Chayslin duga temple (left) by steel frame, Vatsala temple (center) was destroyed and Yaksheshvara temple (right) survived (photo by T. Ohsumi).

Fig. 3.3 This sikhara was demolished (photo by T. Ohsumi).

Fig. 3.4 Chasin Mandapa (left) and Siddhilakshmi Shikhara (right) (photo by T. Ohsumi).

Before the earthquake After the earthquake

Fig. 3.5 The Fasi Dega was destroyed (photo by T. Ohsumi).

Fig. 3.6 Nyatapola temple (left) and Bhairavnath temple (right) are no damage (photo by T. Ohsumi).

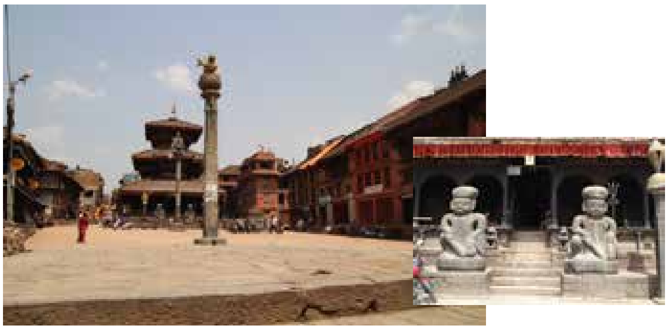

Fig. 3.7 Main Dattatreya temple at Dattatreya Square (left), two watchmen / guardians hold Grakata (right) (photo by T. Ohsumi).

Fig. 3.8 This temple collapsed in 1934 earthquake, but has not been rebuilt (photo by T. Ohsumi).

3.2 Lalitpur/ Patan

In Lalitpur of the Royal Palace, Patan is "Lalitpur" in Sanskrit, is called "*Yela*" in Newari, it means the city of beauty.

The Patan palace was renovated with assistance from the Kathmandu Valley preservation trust (KVPT) and the Sumitomo Foundation in 2013.

Thus, in Patan, 2015, after the earthquake, this place had only partial damage at Gajur and Baymvah (**Fig. 3.9-11**).

Krishna Sikhara was survived. Jagannarayan Temple (left), Vishnu Temple (ceter) and Narasimha Sikhara from 1598 (front) were survived (**Fig. 3.12**).

3.3 Kathmandu

The old palace structures in Kathmandu's Durbar Square, which had not undergone renovations, had severe damage during the earthquakes (**Fig. 3.13**). In the photo on the left, the white structure is about 150 years old, built during the Rana Dynasty. In the photo on the right side, the four-tiered brown temple is about 300 years old, constructed during the Gorkha Dynasty.

The Kasthamandap temple was built by king Laxmi Narsingha Malla in the early 16th century. The whole temple was made from a single tree. Kasthamandap is said to be the etymology of Kthmandu. The earthquake on April 25, 2015 caused severe damage to this temple and it collapsed (**Fig. 3.14**).

At places along the Kathmandu Ring Road, reinforced concrete (RC) frame buildings were damaged by tilting; however, most of the building damage in the city occurred in masonry buildings. At Gongabu, northwest of the Ring Road, many RC buildings were damaged; most of these were

Fig. 3.9 Taleju three-tiered temple Lalitpur (photo by T. Ohsumi).

Fig. 3.10 Patan 2015, after the earthquake, this place had partial damage at Gajur and Baymvah (right) (photo by T. Ohsumi).

Fig. 3.11 Renovation of the structure and the cover of the roof was carried out in 2011.
a: top left Installation of timber rafters,
b: hand wood planking,
c: waterproof membrane,
d: traditional terracotta roof tiles on a mud-bed
(from Information plate of Patan Museum).

Fig. 3.12 Jagannarayan Temple (left), Vishnu Temple (ceter) and Narasimha Sikhara were survived (photo by T. Ohsumi).

Fig. 3.13 Kathmandu Durbar Square after the earthquake (right), before earthquake (left) (photo by T. Ohsumi).

Fig. 3.14 Kasthamandap temple before the earthquake (*a*) / after the earthquake (*b*) (photo by T. Ohsumi).

Fig. 3.15 At Gongabu, RC frame buildings were tilted (*a,b*). A shear crack in the first flower (*c*) (photo by T. Ohsumi).

Fig. 3.16 At west side of the Ring Road in Kathmandu, RC frame buildings were tilted (photo by T. Ohsumi).

(OpenStreetMap https://www.openstreetmap.org/)

Fig. 3.17 At the branch point of the Bagmati River and the Transformor River, collapsed building fell onto and destroyed the next building (photo by T. Ohsumi).

four to seven story structures. The damage was sometimes greater at locations with soft ground such as deltaic deposit near river branches (**Fig. 3.15**); however, some damage was also likely to have been caused by inappropriate construction methods. At Sitapaila, west of the Ring Road, some RC building collapsed at locations where the ground conditions on terraces were a bit stiff. At Balkhu, southwest of the Ring Road, RC frame buildings were tilted. This is near the confluence of the Bagmati and Balkhu rivers, where collapsed buildings fell onto and destroyed a neighboring building (**Fig. 3.16**). The ground conditions in Balkhu were soft because of the presence of riverbed sediments.

3.4 Madhyapur Timi

In the JICA (2002) report, building types were classified for the whole Katmandu. The investigation was mainly based on visual observations (**Fig. 3.18**:upper). In newer building areas (**Fig. 3.18(*a*)**), the damage has been reduced in the building of the RC structures. The core area located on a small hill (**Fig. 3.18(*b*)**), the houses had been destroyed in 1934 rebuilt and again received severe damages.

3.5 Sanhkhu

Sankhu is an old town and locating on a small hill in the north east part of the Kathmandu Valley. Houses damaged by the earthquake have been demolished with the support of Canadian Forces relief operations in Sankhu. Heavy equipment was brought for this purpose from Canada. In general, RC buildings were partially damaged, whereas masonry buildings were severely damaged.

The houses damaged by the earthquake have been demolished with the support of the Canadian Forces in Sankhu. Heavy equipment was brought from Canada (**Fig. 3.19**). The difference in damage as a result of building type was remarkable. Damage in Sankhu was extensive. Brick and cement mortar houses without RC columns experienced a lot of damage. In contrast, the damage to RC structures – particularly those erected in recent years – was generally minor. These structures were mainly five to six story buildings. In contrast, many of the non-engineered masonry structures that experienced complete collapse or partial damage were two to four story buildings in Sankhu (**Fig. 3.20**). Damage in non-engineered masonry structures was initiated by vertical cracks in the corners of the buildings, which contained no RC columns (**Fig. 3.21(*a*)**), the outer wall structures of such buildings were generally burned brick with cement mortar joints to withstand rain. In several cases, the inner walls of buildings are adobe bricks with mud mortar (**Fig. 3.21(*b*)**).

Fig. 3.18 The building type classification map in Thimi, Sano Thimi (*a*) and Old Thimi (*b*) (photo by T. Ohsumi).

Fig. 3.19 In Sankhu, heavy equipment from Canada (photo by T. Ohsumi).

Fig. 3.20 RC buildings were partially damaged, the difference appears remarkable in Sankhu (photo by T. Ohsumi).

Fig. 3.21 A vertical crack in a brick masonry wall was generated from the corner (*a*). Structures having no RC columns on the corner (*b*) (photo by T. Ohsumi).

4. Landslides, Suburbs, Rural Areas

4.1 Landslides

A numerous huge slope failures which occurred in the mountainous area buried villages and valleys, and provided the loss of many lives. We visited a landslide zone in Ramche, and it is located in the northwest of Kathmandu city in a mountainous area. Many of fallen rocks were on the roads, also we encountered a bus that hit by falling rocks (**Fig. 4.1**). Thick talus is deposited in the landslide area in Ramche, in Rasuwa district (**Fig. 4.2**). The town is located at an altitude of 2,060 m. There are houses that had been caught in a landslide, but the damage was limited. However, the whole scope of the slope failures is not clear at the present time, because any detailed and total survey in the mountainous area has not been carried out. Thus, causalities will in-crease as they are found.

Thick talus is deposited in the landslide area in Ramche, in Rasuwa district. The town is located at an altitude of 2,068 m. There are houses that had been caught in a landslide, but the damage was limited. However, the whole scope of the slope failures is not clear at the present time, because any detailed and total survey in the mountainous area has not been carried out. Thus, causalities will increase as they are found.

Fig. 4.1 Bus was hit in falling rocks in Dhikure,on Baglung Rajmara High way (photo by T. Ohsumi).

4.2 Suburbs and Rural areas

The number of casualties was concentrated to the northeast of Kathmandu Sindhupal Chok district. We visited at Charikot, in the Bhimeshwar Munic-ipality, roughly 50 km east of Dhulikhel. The town is located at an altitude of 1,550 m. The name of the district Dolakha came from Dolakha Town, which is situated northeast of the capital Charikot. These areas had many casualties. According to the locals, the large aftershock felt stronger than the main shock. This is understandable as the aftershock's hypocenter is located just

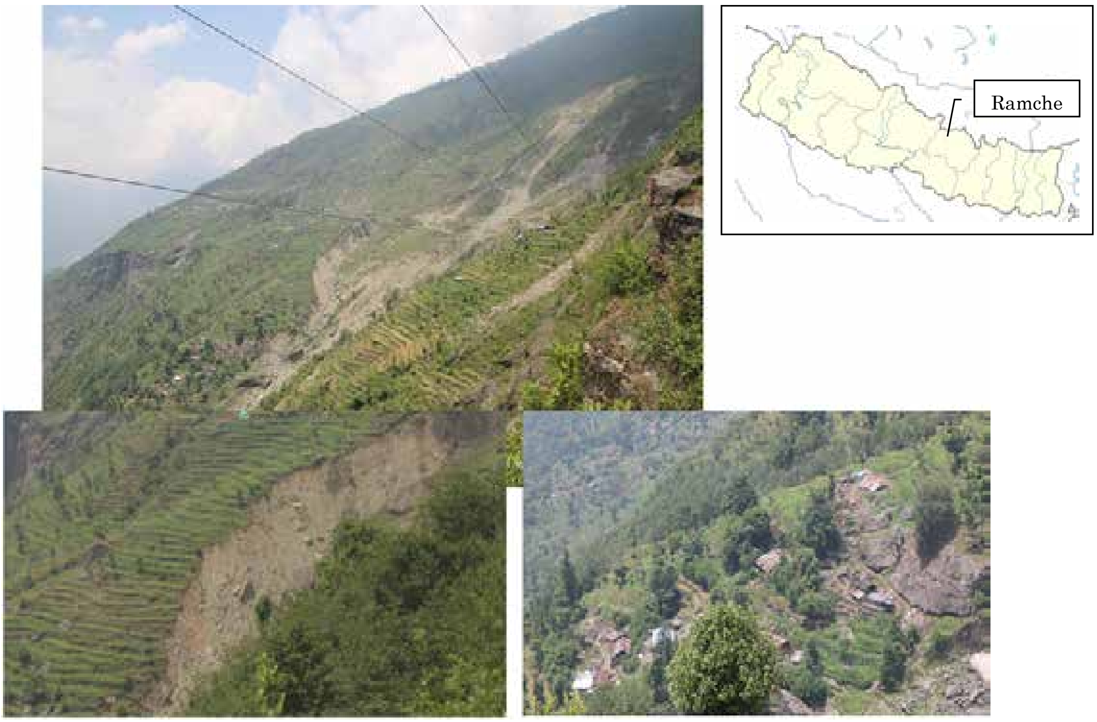

Fig. 4.2 Thick talus is deposited in the landslide area in Ramche (photo by T. Ohsumi).

below this area. Many houses collapsed in the aftershock (**Fig. 4.3**).

Urban and rural housing is significantly different. In the suburban and rural areas where there are many stone houses, a lot of damage occurred. The collapse of heavy stones used in house construction, resulted directly in deaths and property destruction.

In Dolakha district, adobe style houses collapsed. Primarily, adobe houses collapsed as a result of cracks in the gables and corner foundations as a result of ground motion. Many adobe style houses were broken at their gables. Stone houses could also collapse as a result of delamination. Stone style houses also collapsed by delamination.

According to the Nepal Police statistics as of 22 June 2015, more than 500 thousand buildings and houses were damaged – and about half of those collapsed; that number is now increasing (**Fig. 4.4**). First, the dominant rural housing style in the area consists mainly of stone or adobe masonry as well as mud mortar masonries. The collapse of heavy stone buildings killed many. The damage to houses in the mountainous region was typically concentrated in non-engineered structures. In rural areas, unreinforced masonry, sourced from regionally available materials, was the main construction material. Regardless of the masonry material used, serious damage occurred with houses as a result of masonry cemented with mud mortar. This housing construction method also exists in urban areas, primarily for constructions undertaken more than 30 years ago. In the rural areas, this type of housing is still the most popular method of housing construction. Thus, the retrofitting of low-cost earthquake-damaged housing without the consideration of engineering standards is a key issue.

Fig. 4.3 Adobe style houses collapsed at the gable part in Charikot, Bhimeshwor Municipality (photo by T. Ohsumi).

Fig. 4.4 Stone style house in Charikot, Bhimeshwor Municipality (photo by T. Ohsumi).

5. Disscution

According to the statistics by The Nepal Police on 22 June the number of deaths 8,660 and injured 21,952 for the main shock and deaths 172 and injured 3,470 for the aftershock (**Table 1**). It was also reported that more than 5 million buildings and houses were damaged and about half of those had which collapsed, number is increasing now

Why this area had concentrated casualties?

First, the dominant rural housing style in the area consists mainly of stone masonry. The collapse of heavy stone buildings killed many. The damage to houses in the mountainous region was typically concentrated in non-engineered structures. In rural areas, unreinforced masonry, sourced from regionally available materials, was the main construction material. Regardless of the masonry material used, serious damage occurred with houses as a result of masonry cemented with mud mortar. This housing construction method also exists in urban areas, primarily for constructions undertaken more than 30 years ago. In the rural areas, this type of housing is still the most popular method of housing construction. Thus, the retrofitting of low-cost earthquake-damaged housing without the consideration of engineering standards is a key issue.

Second, this earthquake involved major high-frequency (1 Hz) seismic energy that can be observed in the earthquake waveforms. Yagi and Okuwaki, (2015)[7] shows an earthquake rupture model for the 2015 main shock. This model was developed by inverting teleseismic P-wave data using a novel formulation that takes into account the uncertainty of the Green's function using Yagi and Fukahata (2011)[8], which uses the waveform inversion of waveform (time-series) data from IRIS (the Incorporated Research Institutions for Seismology). The fault length and width of the rupture plane run in an east-west orientation for about 150 km, including Kathmandu and the 120-km-long region from north to south with a slip of 4.1 m or more.

Yagi *et al.* (2012)[9] developed a new back-projection method that uses teleseismic P-waveforms to integrate the direct P-phase with reflected phases from structural discontinuities near the source and used to estimate the spatiotemporal distribution of the seismic energy release of the 2015 Gorkha Nepal Earthquake from the IRIS GSN (Global Seismographic Network) and FDSN (International Federation of Digital Seismograph Networks) Information data.

The area where significant high-frequency (1 Hz) seismic radiation extended east-southeast from the hypocenter corresponds to the region where the main slip is distributed near the Kathmandu Valley. However, the main slip is comparatively small near the hypocenter. Slip distribution determined by source inversion analysis is shown in a contour map. The area is north of the Kathmandu Valley and located near the North Bagmati scenario earthquake model.

The major high-frequency (1 Hz) seismic radiation area by hybrid back-projection analysis is read from Yagi's analysis and shown by pink colored square region. The area is north of Kathmandu Valley and near the North Bagmati scenario earthquake model. The major high-frequency (1 Hz) seismic radiation caused much of the damage to buildings in the Kathmandu Valley.

Table 1 Human Damage Information by the Earthquake.by Nepal Police.

Human Damage						
Area		Death	Injured	Under treatment	Identified dead bodies	To be identified dead bodies
Arrea	KV	1,721	11,044	46	1,707	12
	Easten Region	55	323	1	55	0
	Central Region	6,425	6,348	79	6,417	2
	Western Region	457	1,100	720	457	0
	Mid-West Region	2	22	1	2	0
	Far-Western Region	-	2	-	-	0
Total		8,660	18,839	847	8,638	14

What is effective method for brick masonry structure?

A mud mortar, which is especially low adhesive strength, adhesion between the material of housing is reduce during earthquake duration time. A brittle material or structure fractures or suddenly breaks while subjected to bending, swaying, and deforming. The mud mortar avoids the brittle structure due to the little tendency to deform before it fractures. A typical low-story part of earthquake damaged housing causes shear failure of masonry wall. Typical failure pattern of non-engineered housings are out of plane by poor bonding strength (**Fig. 5.2**). A stone masonry building with an RC lintel band that survived this earthquake.

According to "Guidelines for Earthquake Resistant Non-Engineered Construction" [10], horizontal bands or ring beams show detail (**Fig. 5.3**).

The most important horizontal reinforcing is through reinforced concrete bands provided continuously through all load bearing longitudinal and transverse walls at plinth, lintel, and roof eave levels, as well as at top of gables according to requirements as stated hereunder:

1) Plinth band: This should be provided where the soil is soft or uneven in its properties as happens in hill areas. It also serves as damp proof course. This band is not too critical.
2) Lintel band: This is the most important band and is incorporated in all door and window lintels. Its reinforcement should be extra to the lintel band steel.
3) Roof band: This band is required at eaves level of pitched roofs and also below or level with suspended floors which consist of joists and flooring elements, so as to properly integrate them at ends and fix them into the walls.

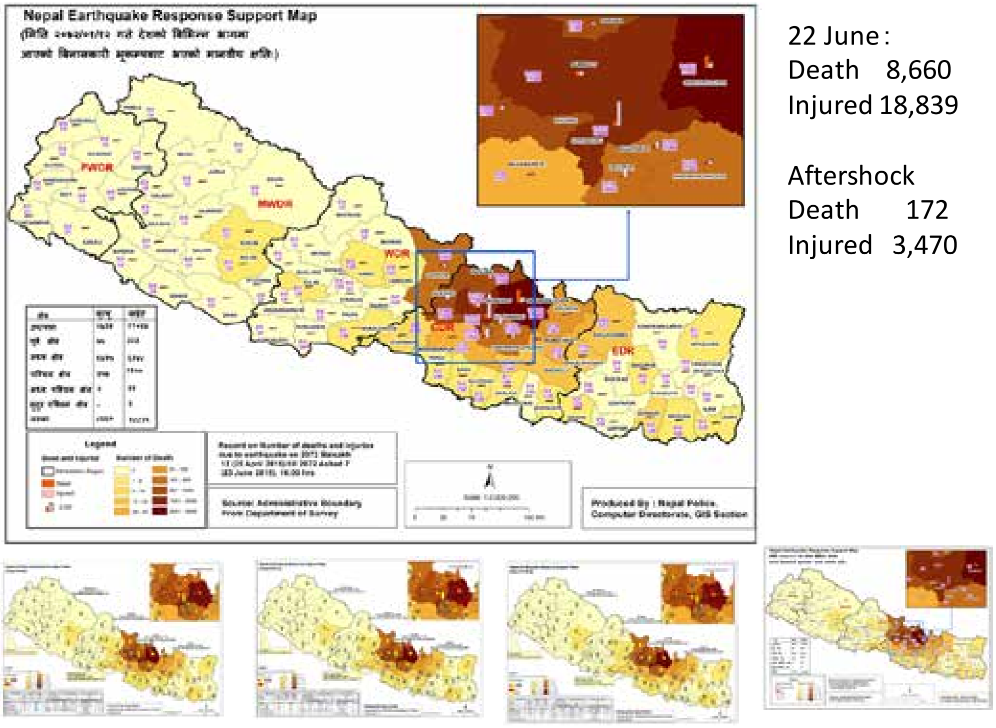

Fig. 5.1 Casualties and injured people by Nepal Police.

Fig. 5.2 Typical failure pattern of Non-engineered housings left: Nuwakot, right: Ksthmandu (photo by H. Imai).

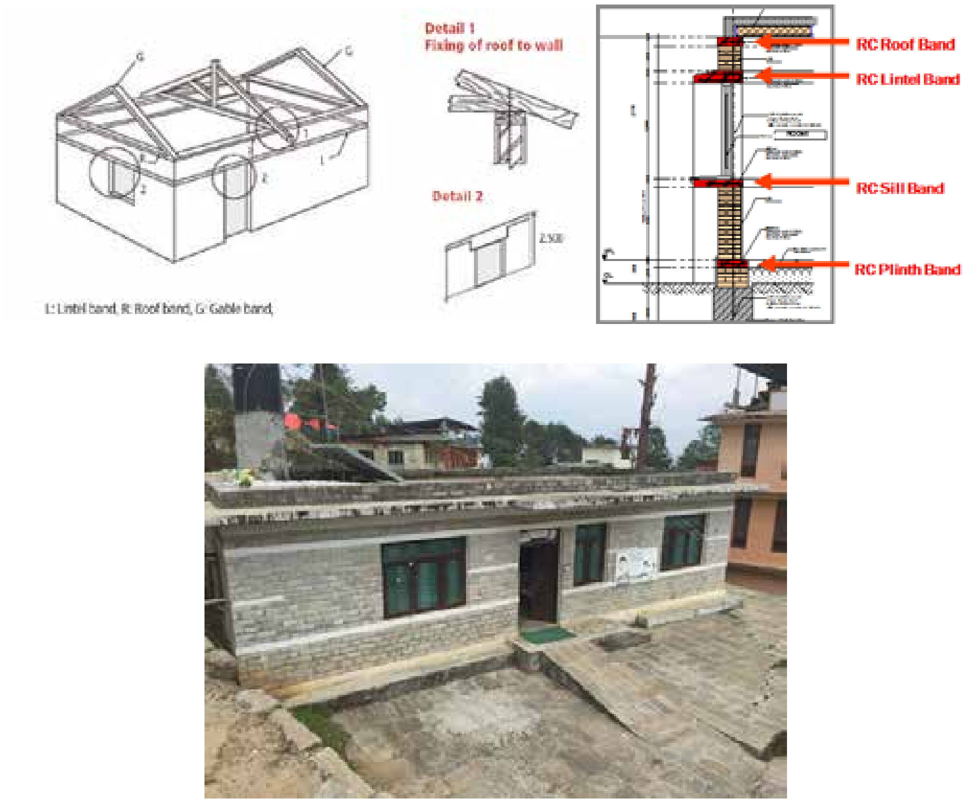

Fig. 5.3 Seismic RC band for stone and brick masonry (NSET promoted in Dolakha, Nepal) (photo by H. Imai) (upper figure from Arya (2013) [10]).

6. Characteristic of This Earthquake Summary and Conclusions

1) Westside of the Ring Road in Kathmandu, RC frame buildings were tilted. The building damage was caused by the soft ground area on the river branch.
2) RC buildings were partially damaged the difference appears remarkable. The brick and cement mortar houses without RC columns had a lot of damage. Structures having no RC columns on the corner, a vertical crack in a brick masonry wall was generated.
3) The number of casualties is concentrated in the north-east of Kathmandu Sindhupal Chok district. Many houses collapsed in the aftershock. Urban and rural housing is significantly different. In the suburban and rural areas there are many stone houses, a lot of damage occurred. The collapse of heavy stones used into house construct, took away many.
4) Three kings in the Kathmandu valley palaces were in Kathmandu, Bhaktapur, and Lalitpur / Patan. The difference between the renovation works done at these palaces was significant (Not for the historic structures of the old royal palace).
5) In the rural areas, stone masonry type of housings are also currently in the people housing construction. Thus, retrofitting of low-cost housing for such non-engineers is a key issue.
6) The major high-frequency (1 Hz) seismic radiation caused the damage to buildings and housing in the north of Kathmandu Valley.

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Chapter 2

Third trip and Forth trip: Investigation of damage in Sankhu and Khokana related to the 2015 Gorkha Nepal Earthquake

1. Introduction

The National Research Institute for Earth Science and Disaster Prevention (NIED) and Japan Aerospace Exploration Agency (JAXA) organized a joint damage survey team. Thread damage survey was conducted for every house in Sankhu on August 17–18, 2015 and in Khokana on August 19–20, 2015 (**Fig. 1**).

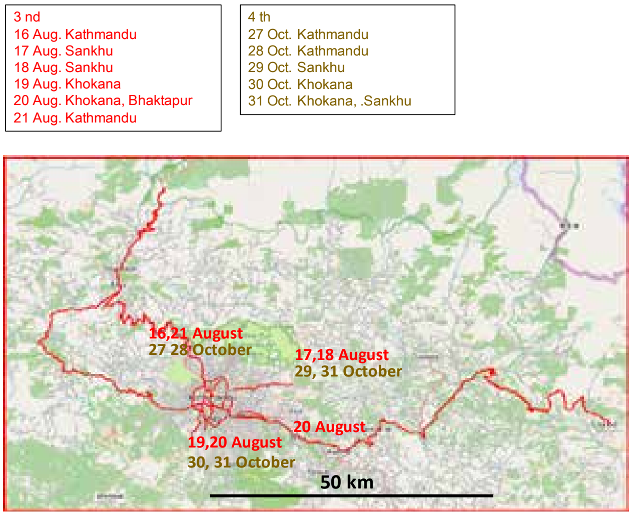


Fig. 1 Survey Route.
(OpenStreetMap https://www.openstreetmap.org/)

At the beginning of this Chapter, we found traditional construction methods are stronger than imagined. Many traditional earthquake-resistance technologies exist in Nepal. This is an important factor in maintaining traditional construction methods to preserve such technologies.

The maintenance of traditional buildings contributes not only to the maintenance of world heritage but also improvements in the earthquake resistance of cities. The problem of the masonry structure and in maintenance is shown in this study.

In Nepal, *Naga* Panchami is a festival in which the Nepali people participate in traditional snake-worshipping rituals. Nepalese people believe that their houses have been the patron by the *Naga* band. Masonry buildings that had installed *Naga* bands survived the 2015 Gorkha earthquake.

Surveys of building types and damage extent were conducted, for every house in Sankhu and Khokana, Kathmandu, after a second survey term. For building types, we used building classification surveys by the Japan International Cooperation Agency, commonly called JICA (2002)[1), 2), 3)]. Building damage magnitudes were classified using European Macroseismic Scale (EMS)-98 (Grunthal, 1998)[4)]. A high-resolution image from March 12 (before the disaster) was obtained from Google Earth™ prior to the survey [5), 6)]. This image was used to identify the position of each building before the earthquake, based on which the damage to each building was estimated in accordance with EMS-98.

With the above approach, we determined damage in Sankhu and Khokana related to the 2015 Gorkha Earthquake in core areas, using the damage function indicated by JICA (2002) [1), 2), 3)].

2. Traditional Construction Methods in Kathmandu Vally

2.1 Chowks, a type of courtyard

The traditional method of brick making is stronger than imagined. It has been indicated that over 40 % of traditional masonry survived the earthquake of 1934 in the strong motion area. It is considered that buildings surrounding a courtyard have high rigidity. This is important to show the usefulness of saving the lost courtyard **Fig. 2.1** and **2.2** shows typical courtyard in Lalitpur and Bhaktapur.

Fig. 2.1 Building with a central courtyard/chowk in Lalitpur (photo taken in 2001).

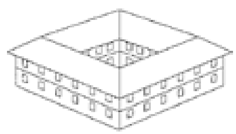


Fig. 2.2 Connected structures in Bhaktapur.
(photo by T. Ohsumi, taken in 2001)

Fig. 2.3 Traditional buildings are gradually becoming less common as a result of rebuilding.
(photo by T. Ohsumi, taken after earthquake in Sankhu)

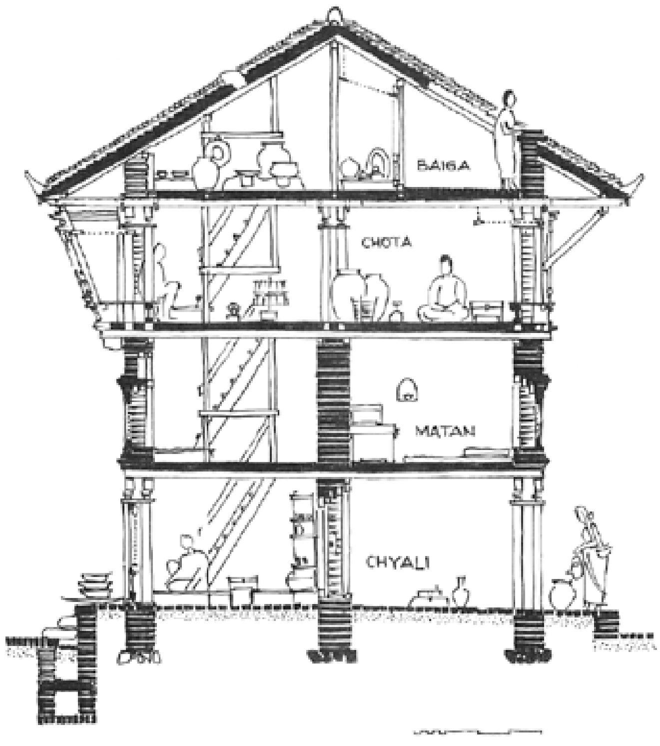


Fig. 2.4 Typical cross section of a multiple-story building.
(Courtesy of Assistant Prof. Ram Prasad Suwal with the Nepal Engineering College)

A *chowk* is a type of courtyard that is common in the community of Newar in Nepal. The *chowk* is characterized by a square or rectangular space surrounded by buildings on all sides. The surrounding buildings are built on a raised platform, called *falcha*. Opposite the main entrance on the ground floor is an area dedicated to the Guthi - Social Unify and other gods with idols of deities. The chowk structure is excellent with respect to earthquake resistance. However, these traditional buildings are gradually becoming less common as a result of rebuilding (**Fig. 2.3**).

2.2 Why are most masonry buildings four-story structures?

In urban core areas, four-story buildings dominate, and more than a third of the buildings are five stories or higher. The construction of the Nepalese traditional four-story house is shown in **Fig. 2.4**. These are mainly brick masonry structures, but many of them have been extended vertically by adding additional stories to the original three- or three and a half-story buildings. In addition, many of them are divided vertically for the use of separate families because of the local custom of succession of property. This contributes to higher seismic risk, even if one does not consider the poor building technology actually adopted for the construction.

2.3 The timber repair

The traditional method of construction, which does not use metal with timber (**Fig. 2.5**, **2.6**) has prevented degradation for a long time. Comparison of colonnade peristyle Patan Royal Palace show in 2001 (**Fig. 2.7**) and in 2015 (**Fig. 2.8**). This type of construction should be repaired using traditional methods without resorting to modern methods. **Fig. 2.9** shows a house's peristyle colonnade and an indoor column with a sub-beam. **Fig. 2.10** shows timber lattice replacements. New timber latticework has been fabricated to replace damaged or lost elements.

This traditional construction method resist motion throughout the structure during earthquakes. However, this method needs to translate all the inertia. The traditional structures caused brittleness transformations and defective corners of the structures related to the 2015 Gorkha earthquake (**Fig. 2.11**, **2.12**). Reinforcement with such components as hold down hardware and battledore bolts is indispensable.

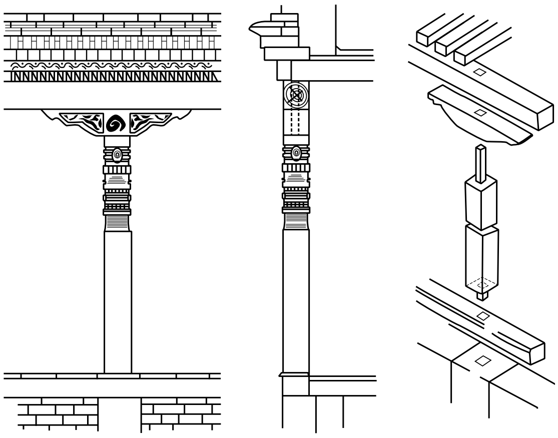
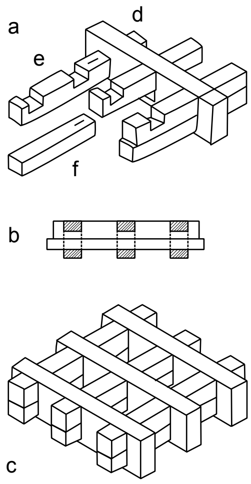


Fig. 2.5 Timber technology [1].



- Detail of opening canage - a: exploded, perspective; b: transversal section; c: perspective of assemblage elements; d: main frame; e: secondary frame; f: wedge key.

Fig. 2.6 Columns and sub-beams (parts of the replica temple with EXPO 2005 AICHI JAPAN: photo by T. Ohsumi in 2005).

Fig. 2.7 Peristyle colonnade in Patan (photo by T. Ohsumi in 2001).

Fig. 2.8 Peristyle colonnade in Patan (photo by T.Ohsumi after the 2015 Earthquake).

Fig. 2.9 House's peristyle colonnade and indoor column with a sub-beam in Patan (photo by T. Ohsumi in 2001).

Fig. 2.10 Timber lattice replacements. New timber latticework has been fabricated to replace damaged or lost elements (from information plate at the Patan Museum).

Fig. 2.11 Traditional structures caused brittleness deformations and defective corners of the building related to the 2015 Gorkha Earthquake in Khokana (photo by T.Ohsumi after the 2015 Earthquake).

Fig. 2.12 Temple caused brittleness deformations and defective corners of the temple related to the 2015 Gorkha Earthquake in Patan (photo by T. Ohsumi after the 2015 Earthquake).

2.4 Naga (snake) effect

The serpentine, referring to a snake in Italian, is praised as the incarnation of god as a symbol of the mother of earth and as a life force since the time of Ancient Greece. The brand of the clock and the jewelry feature this serpentine as a motif in traditional jewelry SPAs (specialty store retailer of private label apparel).

Naga pasa in cornice bands of most temples, timber ties set in the walls. These have religious as well as structural meaning. *Naga pasa* (snake mating tie) is very strong tie which is difficult to separate. These ties represent in buildings as tie beams which unites the whole building together. The date of the Naga Panchami in 2015 was August 19. The Nepali people believe on God’s present. Serpent deities are made of silver, stone, or wood, and snakes are painted on walls with cow feces. Residents post pictures of Naga above the doors of their homes to ward off evil spirits (**Fig. 2.13**).

Naga means “snake”. *Naga pokhari* means “snake pond”. *Naga pokhari* (snake or cobra water tanks) are located in the courtyard of each Royal Palace (**Fig. 2.14**). This *Dhunge Dhara* is a traditional stone spout found extensively in Nepal.

Fig. 2.15 shows a *Naga* band on a well in Khokana. Theses *Naga* lead a purity water element. Theses *Naga* represent water element and symbolized as purity.

Fig. 2.16 shows a *Naga* band on an altar in Sankhu. A band, designed by *Naga*, has been installed between the first floor and the second floor in the house, throughout the whole building. There is a *Naga* band in a historical masonry building. Damage in Sankhu was extensive in the 2015 Gorkha Earthquake. However, this type of structure survived (**Fig. 2.17**).

Fig. 2.13 Residents post pictures of *Naga* above the doors to their homes to ward off evil spirits (photo by T.Ohsumi in 2015).

Fig. 2.14 *Naga pokhari* (snake or cobra water tank) in the courtyard of the Royal Palace in Bhaktapur (*a*) and Kathmandu City (*b*) (photo by T. Ohsumi in 2015).

Fig. 2.15 *Naga* band on a well in Khokana (photo by T. Ohsumi in 2015).

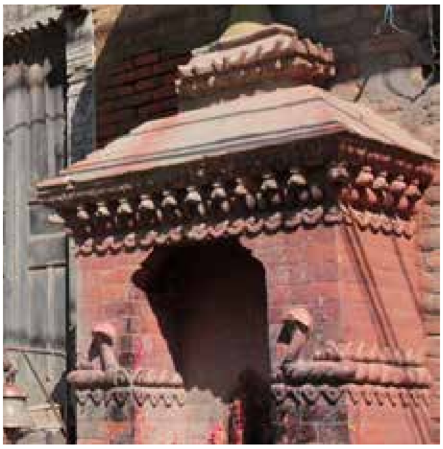


Fig. 2.16 *Naga* band on an altar in Sanhku (photo by T. Ohsumi in 2015).

Fig. 2.17 Building constructed over 100 years ago that was slightly damaged by the Gorkha earthquake. The building has a snake (*Naga*) band surrounding it between the first and second floors (photo by T. Ohsumi, taken after Gorkha earthquake in Sankhu).

2.5 The latticed window and the outer frame effect

A latticed window and an outer frame (*puratva*) surrounds door are reinforced itself the buildings. The window and the door made with a tree have its own stiffness. The wooden frame doing the solid is arranged with the outside wall and the inside. The wooden frame and the door fixed from both sides has secured stiffness in an opening (**Fig. 18** to **20**). Shuttering windows (*Pasahdhi*) consists of a lower panel or planks inserted into a joint and locked in its position by a rail and a movable shutter. The shutter is fastened at the ceiling joints before the rail and panel are removed (**Fig. 21**, **22**).

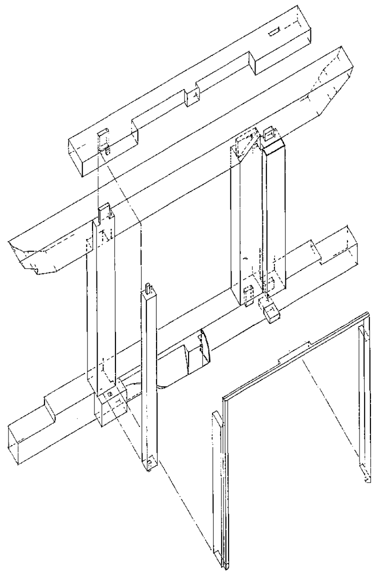


Fig. 2.18 Structural elements of a window (after Gutschow (1987)).

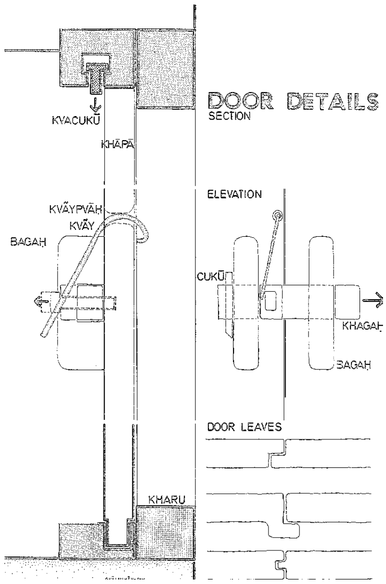


Fig. 2.19 Doorbolts (after Gutschow (1987)).

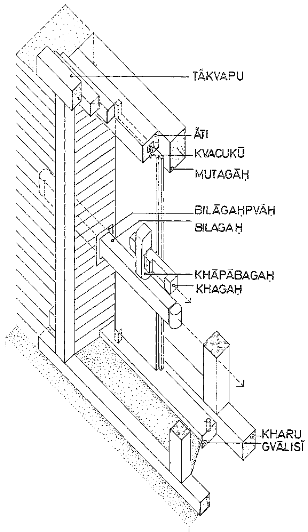


Fig. 2.20 Section of a door: details of sill, lintel, door leaves and bolts (after Gutschow (1987)).

Fig. 2.21 Shuttering window (photo by T. Ohsumi).

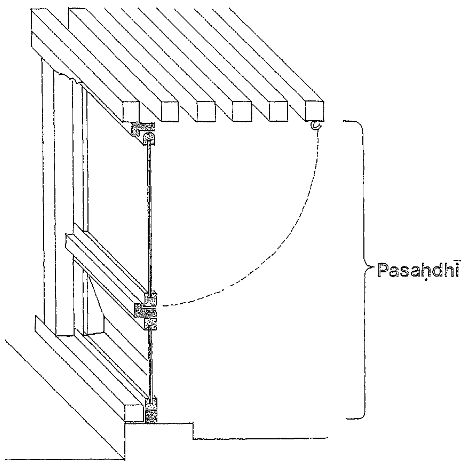


Fig. 2.22 Section of a shuttering window (after Gutschow (1987)).

2.6 The degradation of wall surface

Water rises from underground, and its evaporation deteriorates the wall surface of masonry structures (**Fig. 2.23**, **2.24**). Repair for the brick is required for deteriorates with the prevention of the water rise. **Fig. 2.25** shows the scree of bricks. Sun-dried bricks (adobe) of the interior are seen.

Fig. 2.23 Royal Palace wall in Kathmandu (photo by T. Ohsumi in 2001).

Fig. 2.24 Private house wall in Bhaktapur (photo by T. Ohsumi in 2001).

Fig. 2.25 Scree of bricks. Sun-dried bricks (adobe) of the interior are seen (photo by T. Ohsumi in 2001).

2.7 Chuku Joint

The floor joists are held in position by a chuku (wooden peg) through holes on either side of the wall plate (**Fig. 2.26**, **27**). The chuku is wedged to provide earthquake resistance, but use of the chuku has been dropping in recent housing.

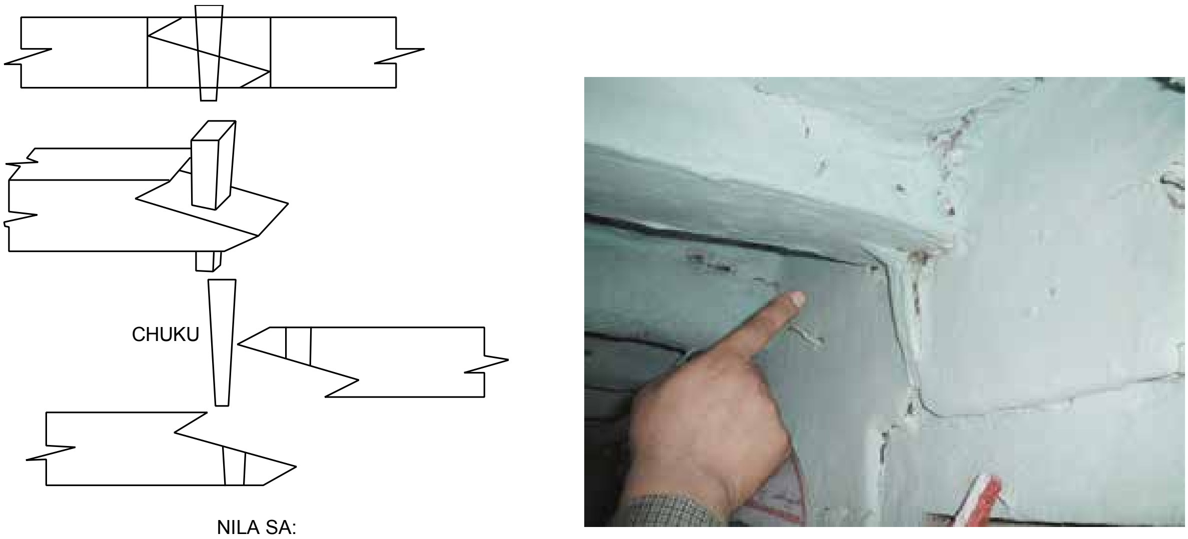


Fig. 2.26 Details of member joints (photo by T. Ohsumi in 2001).

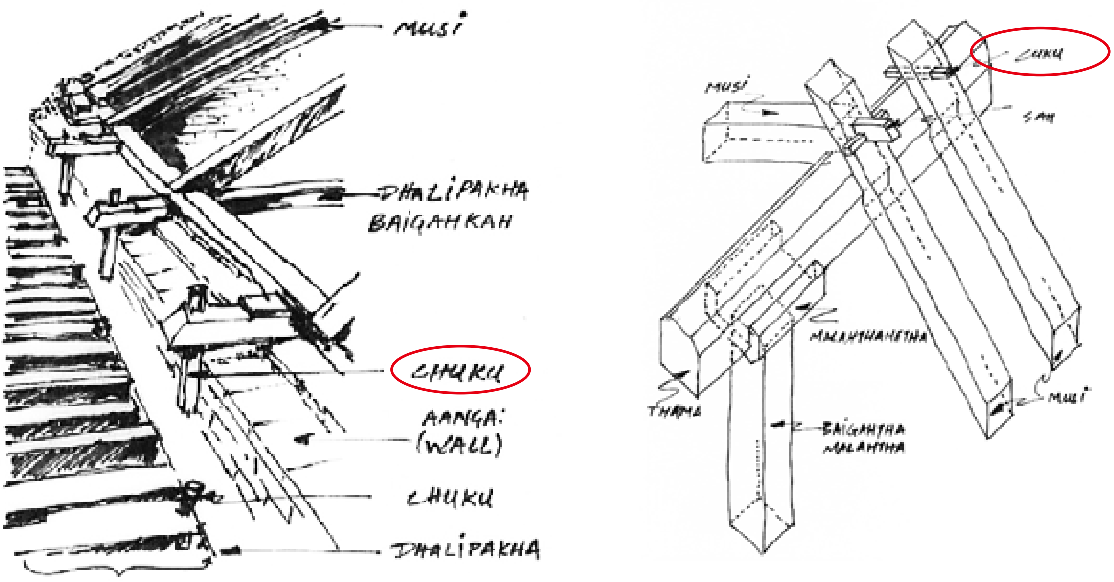


Fig. 2.27 Typical chuku image.
(courtesy of Assistant Prof. Ram Prasad Suwal with Nepal Engineering College)

3. Maintenance Technology

3.1 Roof repair

Soil is put in the roof and prevents heat conduction from sunlight and water resistant to the indoors (**Fig. 3.1**). Though the soil is cured in the construction (**Fig. 3.2**), weeds comes flying by long years and the roof deteriorates. For the infiltration of rainwater, the building deteriorates. The roof renovation is important periodically.

Renovation of the temple's roof was carried out in 2015 (**Fig. 3.3**). **Fig. 3.4** shows a house roof renovation carried out in 2015.

Fig. 3.1 Cured soil for roof (photo by T. Ohsumi in 2001).

3.2 Renovation of the Royal Palace

The Patan palace was renovated with assistance from the Kathmandu Valley Preservation Trust (KVPT) and the Sumitomo Foundation in 2013 (**Fig. 3.5**). Thus, in Patan, after the earthquake, this palace had only partial damage at the top of the structure (Gajur and Baymvah).

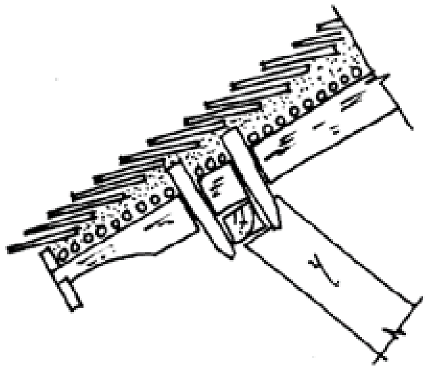


Fig. 3.2 Typical roof cross section.
(courtesy of Assistant Prof. Ram Prasad Suwal with Nepal Engineering College)

Fig. 3.3 Renovation of a temple's roof was carried out in 2015 (photo by T. Ohsumi).

Fig. 3.4 Renovation of a house roof was carried out in 2015 (photo by T. Ohsumi).

Fig. 3.5 Renovation of the structure and the covering of the roof was carried out in 2011:
a: (top left) installation of timber rafters, *b*: hand wood planking, *c*: waterproof membrane, *d*: traditional terracotta roof tiles on a mud bed (from information plate at the Patan Museum)

4. Microtremor Analyses

We had carried out microtremor measurements prior to the earthquake in selected areas. A comparison of the vibration characteristics of the four sides of the buildings provided an evaluation of the stability of the buildings during an earthquake.

4.1 Chowk structures

Microtremor analyses conducted on *chowks* showed response amplitudes that are low for burned masonry (four-storied BM) constructions with a courtyard. Further microtremor measurements were made on a typical courtyard located at Nakabahil (Nagbahal), Lalitpur. **Fig. 4.1** and **Table 4.1** show the predominant frequencies and response amplitudes for the top/bottom ratio (for a four-storied building). The structure appears to have remained in good condition following the earthquake, with the equal building/floor heights providing a rigid fixed structure. A comparison of the vibration characteristics of the four sides of the buildings provides an evaluation of the stability of the buildings during an earthquake. **Fig. 4.2** and **Table 4.2** show the predominant frequencies and response amplitudes for the top/bottom ratio. Predominant frequencies lie between 3.4 and 4 Hz and response amplitudes are 2 to 10. The range in these values is significant. Response amplitudes are high for BM (three-storied) and RC-5 storied buildings. Predominant frequencies are 3 to 4 Hz for BM (three-storied), RC-3 and RC-5 storied buildings. Predominant frequencies are 3 to 4 Hz for BM (three-storied), RC-3 and RC-5 storied

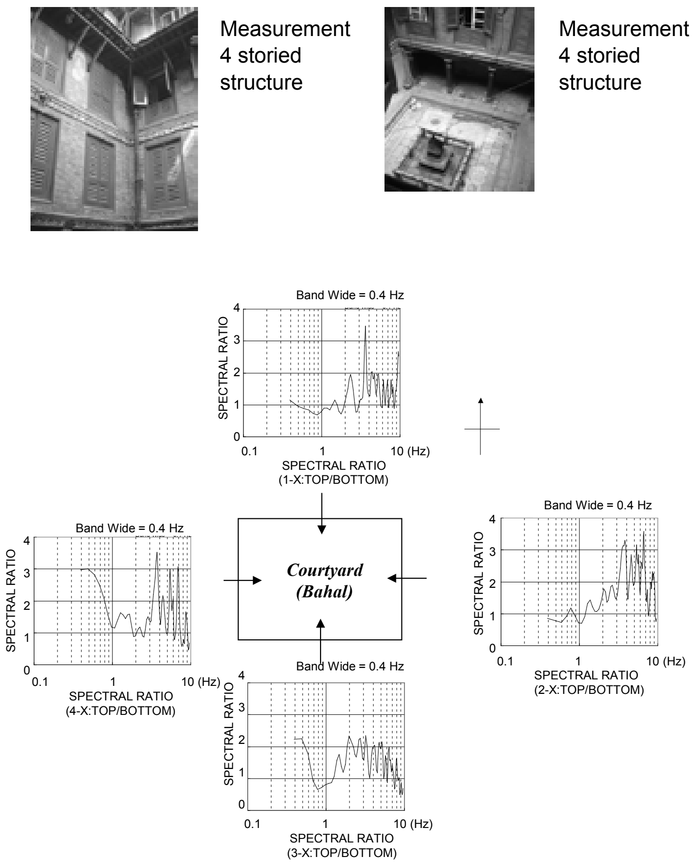


Fig. 4.1 Courtyard (Chowk) microtremor measurements at Nakabahil, Lalitpur.

Table 4.1 Microtremor Resort at Nakabahil (Nagbahal), Lalitpur.

Measurements points	***Response Amplitude***	***Predominant Frequencie***
1 (North)	3.5	3.5 Hz (0.29 s)
2 (East)	3.5	3.8 Hz (0.26 s)
3 (South)	2.3	2.0, 3.2 Hz (0.31 , 0.5 s)
4 (West)	3.5	3.5 Hz (0.29 s)
average	3.2	3.35 (0.30 s)

Table 4.2 Result of measurement.

Structural Type	Response Amplitude (Top/Ground)	Predominant Frequency (Hz)
1) BM: Brick with mud mortar (3 storied)	7.52	4.10 (0.25 s)
2) BM: Brick with mud mortar (courtyard) (4 storied)	3.2	3.35 (0.30 s)
3) RCL: RC frame with brick / Low storied (2 storied)	2.1	3.90 (0.26 s)
4) RCH: RC frame with brick / High storied (5 storied)	10.1	3.52 (0.28 s)

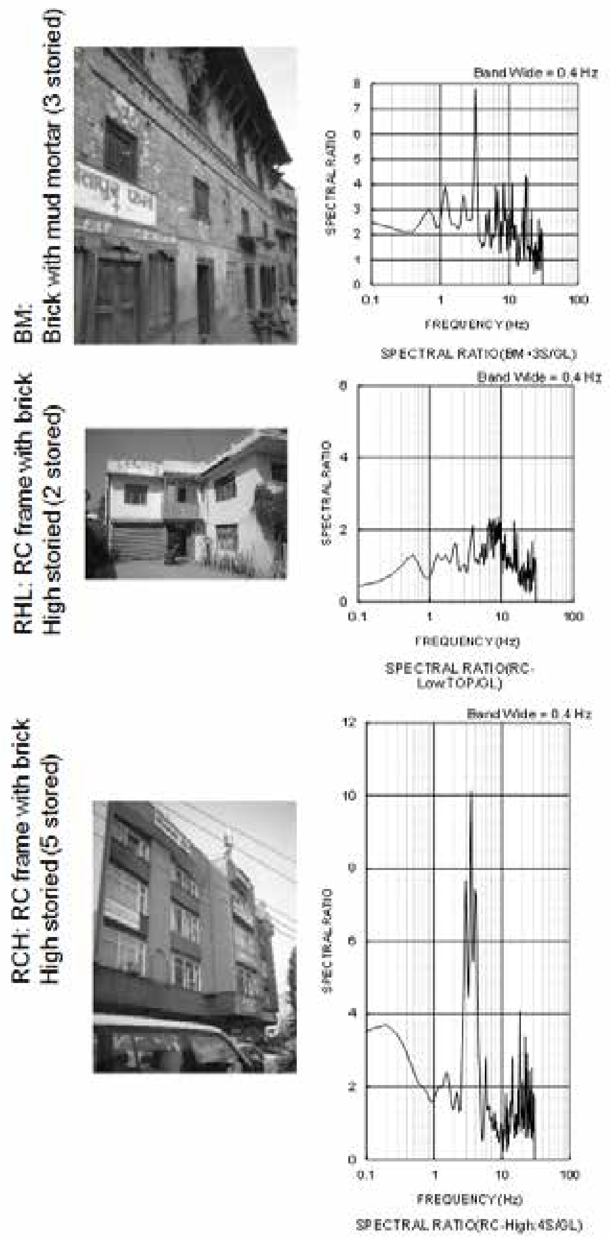


Fig. 4.2 Microtremor measurements of structure vibration.

Fig. 4.3 Bhaktapur before / after the earthquake (Photo. by T. Ohsumi), before / after the 1934 earthquake in Bhaktapur (Courtesy of MoHA).

buildings. Response amplitudes are low for BM buildings with a courtyard and RC-3 storied buildings. Predominant frequencies are 5 to 10 Hz for BM and RC-3 storied buildings. These results reasonably show that RC buildings with a greater number of stories will be more vulnerable than RC buildings with fewer stories, and also that BM structures with courtyards will be stronger than three-storied BM buildings. It was proven that the response amplitudes are low for a sound BM construction with a courtyard. Traditionally made BM structures are stronger than expected and generally will not experience pancake destruction like a weak RC frame structure might experience. As indicated, over 40 % of traditional masonry structures survived the 1934 earthquake – even in the strongly shaken area. It would appear that a building surrounding a courtyard with a symmetrical shape has high rigidity. These results might show the usefulness of preserving the traditional courtyard constructions. Thus, traditional bahals are observed to have excellent earthquake resistance. However, these traditional buildings are gradually becoming less common as a result of rebuilding.

4.2 Why did the brick and wood 55 Window Palace survive in Bhaktapur?

Bhaktapur's Durbar Square is a conglomeration of pagodas and Sikhara style temples grouped around the 55 Window Palace, which is built of brick and wood (**Fig. 4.3**). This temple was undamaged by the earthquake. In contrast, during the 1934 Earthquake, Chyasilin Mandap was completely destroyed. Architects Götz Hagmüller and Niels Gutschow set about rebuilding this temple using metal reinforcement funded by GTZ. As part of this refurbishment, we conducted microtremor measurements for this temple before the earthquake. **Fig. 4.4** shows the inside of the 55 Window Palace. **Fig. 4.5** shows the response amplitudes for the top/bottom ratio. The predominant frequency was 4.2 Hz (a period of 0.24 s).

4.3 What is a suitable predominant frequency for a typical temple?

During "Expo 2005 Aichi Japan", the Nepal pavilion consisted of a replica of the Harati Mata Temple in Swayambhunath, which is characteristic of a restored temple built in a traditional architectural style of the 14th to 15th centuries in Nepal. The Harati Mata Temple survived this earthquake. **Fig. 4.6 (*a*)** shows the Harati Mata Temple in Swayambhunath. **Fig. 4.6 (*b*)** shows the microtremor measurement point of the replica temple. **Fig. 4.6 (*c*)** shows the response amplitudes for the top / bottom ratio. The predominant frequency was 3.2 Hz (a period of 0.31 s).

Comparison of the typical predominant frequencies of Nepal structures and this earthquake

Fig. 4.7 shows the predominant periods and the Fourier spectrum of the main shock. Predominant frequencies lay between 0.25 and 0.32 s, except for two-storied RC structures. However, the predominant period of the main shock was 0.5 s for the low-period high-frequency range. As a result, many structures avoided resonance vibrations.

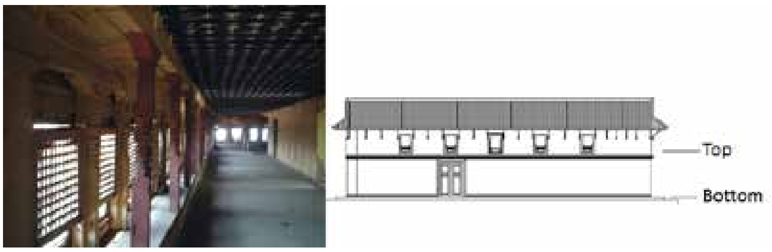


Fig. 4.4 Inside of the 55 Window Palace from The microtremor measurement point at Bhaktapur's Durbar Square (photo by T.Ohsum).

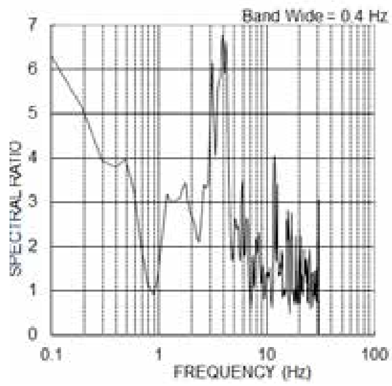


Fig. 4.5 Microtremor measurements of the Window Palace.

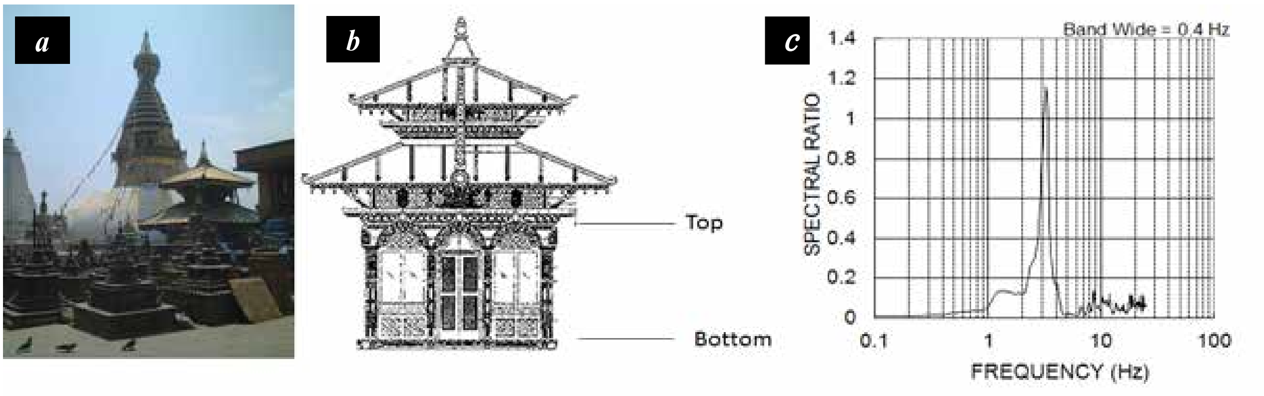


Fig. 4.6 Harati Mata Temple in Swayambhunath: (*a*: Photo.by T. Ohsumi), Microtremor measurement point of the replica temple: (*b*): Broacher of EXPO 2005 AICHI JAPAN), Microtremor measurement of the replica temple: (*c*).

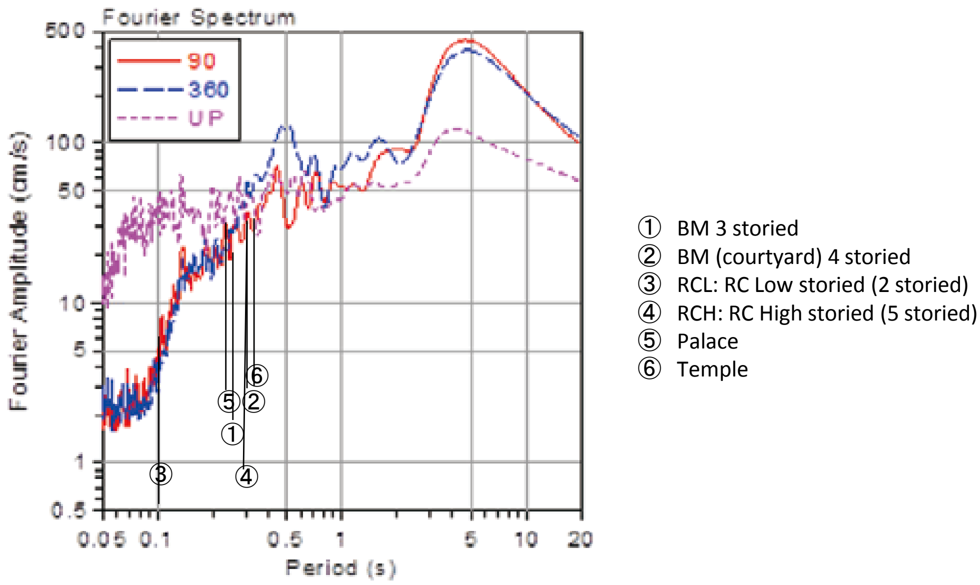


Fig. 4.7 Comparison of the typical predominant frequencies of Nepal structures and the Fourier spectrum of the main shock.

5. Building Damage to Houses in Core Areas

Surveys of building types and damage extent were conducted on August 17–18 and October 28–31, 2015, for every house in Sankhu and Khokana, Kathmandu, after a second survey term. For building types, we used building classification surveys by the Japan International Cooperation Agency, commonly called JICA (2002)[1), 2), 3)]. Building damage magnitudes were classified using European Macroseismic Scale (EMS)-98 (Grunthal, 1998)[4)]. A high-resolution image from March 12 (before the disaster) was obtained from Google Earth™ prior to the survey[5), 6)]. This image was used to identify the position of each building before the earthquake, based on which the damage to each building was estimated in accordance with EMS-98.

5.1 Traditional buildings

The magnitude 8.4 (M_w) Bihar Earthquake in the Kathmandu Valley on January 16, 1934 was of historical strength. Near the earthquake epicenter in the eastern part of Nepal, near the Indian border, there were more than 10,000 dead or missing. January 16 has been declared *National Earthquake Safety Day*, as a memorial in Nepal.

Some buildings survived the Bihar Earthquake, as did some in the 2015 Gorkha Earthquake at Sankhu. Our team investigated the superiority of quake resistance of historical buildings. Building structure types were classified as “well-built,” using a type of brick with mud mortar.

One of the aforementioned buildings (**Fig. 2.17**), which is more than 100 years old, was slightly damaged by the quake. This building has a snake (*Naga*) band surrounding the entire building between the first and second floors. This band is made of wood and is effective in restricting brick structure. **Fig. 5.1** shows a building with little damage, which is also more than a century old. This building underwent expensive improvement for earthquake resistance, including mixing plaster with mud joints.

Fig. 5.1 Building that was over 100 years old, showing little damage (photo by T. Ohsumi, taken after Gorkha earthquake in Sankhu).

6. Building Types in the Kathmandu Valley

Hazards and damage were analyzed in a study on earthquake disaster mitigation in the Kathmandu Valley (JICA, 2002). To estimate damage to buildings from the earthquake, a building inventory, especially one with the distribution of buildings by structural type, is necessary. Building structure types were grouped into the following seven classes based on the inventory.

- ST: Stone
- AD: Adobe
- BM: Brick with mud mortar, poorly built
- BMW: Brick with mud mortar, well built
- BC: Brick with cement or lime mortar
- RC5: Reinforced concrete (RC) frame with masonry of four stories or more
- RC3: RC frame with masonry of three stories or less

According to the inventory, we determined building types and their distribution in the settlement types of Kathmandu Valley. The main types are ST, AD, BM, BC and RC. Newer types (BC and RC) are predominant in the central and rapidly developing areas, and other types (ST, AD and BM) are predominant in rural or older core areas with dense population.

Additional onsite surveys and aerial photo interpretation, combined with results of the inventory, provided the predominant types and their proportions for each small cell of 500 m × 500 m (**Fig. 6.1**). This was used for vulnerability assessment.

Results of a building age survey revealed the current trend of building construction; there was an increase in newer structure types and a decrease of older types. The introduction of cement and sand some 30 years ago significantly changed building construction methods.

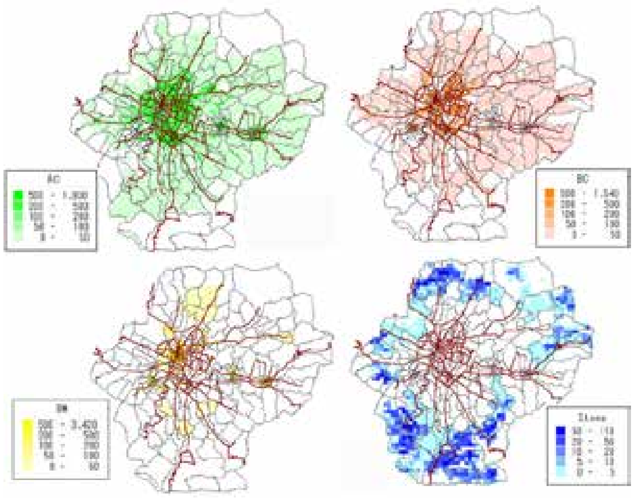


Fig. 6.1 Predominant type of buildings (JICA 2002)[1), 2), 3)] Classification color shows number of a building.

Most buildings have problems of earthquake resistance, as mentioned below.

a) RC

RC buildings have been the most commonly constructed in the last 30 or 40 years in urban areas. Although most building owners and constructors believe that RC buildings are safer and sufficiently strong, most buildings were designed without a structural engineer and were built with supervision by unskilled craftsmen or masons who had no fundamental practice or structural knowledge of RC work. The initial plan including such items as the size of columns and beams was probably for three-story buildings, but current RC buildings extend four to six stories without strengthening of columns and beams. This may be attributed to rapid increase of the urban population. Furthermore, floors of the second and upper stories at roadsides extend beyond the floors of lower stories. Walls of the widened floors are supported by cantilever beams and are located outside the RC frames. The latter case has particularly great fragility in case of a great earthquake.

b) BC and BM

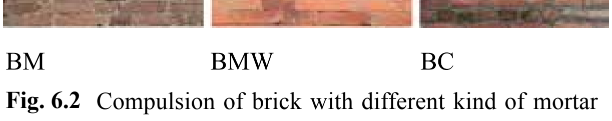
Fig. 6.2 shows a comparison of brick with different kind of mortar as BM, BMW, BC.

BC buildings, also constructed in the past 30 or 40 years, comprise about half the buildings in the valley. This type of building is still weak regarding horizontal rigidity, owing to poor workmanship and lack of structural consideration of the joints from wall to wall, wall to wooden floor and roof, and non-integration of the masonry wall itself. Although buildings of this type that are less than four stories are generally constructed with suitable workmanship and adequate wall balance, those more than four stories tall have great fragility during a powerful earthquake.

BM buildings remain in urban and rural areas. These buildings have very poor horizontal rigidity because of low bond strength and strong absorption of moisture in mud joints, wooden floors and roofs. During a great earthquake, BM buildings of less than three stories appear fragile and those of three or more are even more fragile.

c) AD and ST

AD and ST buildings have great fragility during a moderate earthquake.



BM BMW BC

Fig. 6.2 Compulsion of brick with different kind of mortar as BM, BMW, BC.

6.1 Classification of damage to masonry buildings

Table 6.1 shows EMS-98, which is the European standard. According to this, Grades 1–5 are defined below.

Grade 5: Very heavy structural damage

Grade 4: Very heavy structural and non-structural damage.

Grade 3: Moderate structural damage and heavy non-structural damage

Grade 2: Slight structural damage and non-structural damage

Grade 1: No structural damage and slight non-structural damage

According to JICA (2002)[1), 3)], “Collapse” and “Damage” were defined as below.

Collapse: Collapsed or un-repairable (unsuitable for living)

Damage: Collapsed or un-repairable (unsuitable for living) + 1/2 repairable (available for temporary living)

This standard is difficult to correspond with Nepalese building conditions.

Figure shows the building state of the site after the earthquake.

The upper part of a three-story building with collapsed parts was demolished; only the first floor remained and is usable. **Fig. 6.3** shows the housing situation after the 2015 Gorkha Earthquake. A three-story building was reduced to one story. This building was classified as Grade 4.

Thus, Grade 5 or upper Grade 4 was determined by complete or non-complete collapse.

Grade 3 or upper Grade 4 was determined by moderate structural damage or not enough.

A grade less than 3 was heated for ground truth distinction by a satellite image, and was assigned a corresponding category.

Table 6.1 Classification of damage to masonry buildings by EMS-98 (Grade1-5)[4].

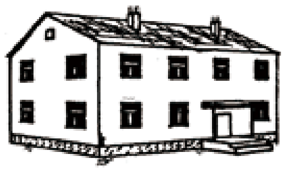
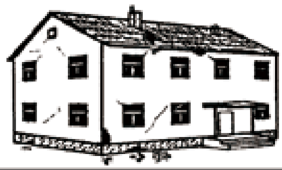
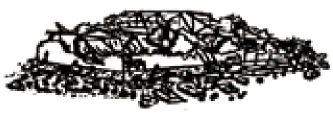
Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

Fig. 6.3 What should be the grade for this building? The three-story building was reduced to one story. This building was classified as Grade 4. (photo by T. Ohsumi, taken after the Gorkha earthquake in Sankhu)

7. Survey of the Degree of Building Damage and Casualties in Sankhu Core Area

Sankhu is an old town on a small hill in the northeastern Kathmandu Valley. It is a municipality in Kathmandu District, which is in Bagmati Prefecture, central Nepal, ~20 km east of the city of Kathmandu.

The National Research Institute for Earth Science and Disaster Prevention (NIED) and Japan Aerospace Exploration Agency (JAXA) organized a joint damage survey team[5, 6]. This damage survey was conducted for every house in Sankhu on August 17–18, 2015 (**Fig. 7.1*a***)[4, 5] and in Khokana on August 19–20, 2015 (**Fig. 7.1*b***)[5, 6], using EMS-98. A high-resolution image from March 12 (before the disaster) was obtained from Google Earth™ prior to the survey. This image was used to identify the position of each building before the earthquake, based on which the extent of building damage was estimated in accord with EMS-98.

7.1 Survey of building damage and casualties in Sankhu core area

This town was the ancient trade route with Tibet. Much Tibetan is living even at present.

The wealthy classes consisted of a large number of historical buildings, and spent funds in housing formerly. However these, buildings lose a source of income by present and decline, and are superannuated, and a renovation is not performed.

Sankhu was on an ancient trade route with Tibet. Many Tibetans still live there.

The wealthy classes occupied a large number of historical buildings, on which they invested funds. However, such investment has ceased and these buildings have declined, become superannuated, and have not been renovated.

In Sankhu, whereas RC buildings were partially damaged, many masonry buildings were severely damaged. The difference in damage between the various building types is remarkable. Generally, the damage in Sankhu was extensive. Brick and cement mortar houses without RC columns had considerable damage, whereas damage to RC structures—particularly those erected in recent years—was generally minor. These latter structures were mainly five- to six-story buildings, whereas many of the non-engineered masonry structures that experienced complete collapse or partial damage had two to four stories.

For the required vulnerability analysis, we recorded building damage, casualty, and census (2010) data from the Shree Shankharpuir municipality office, using transcripts of documents for each ward (**Table 7.1**).

7.2 Survey of building damage and casualties in Khokana core area

Khokana is a traditional old town on a small hill in the southwestern Kathmandu Valley. It is a municipality in the Lalitpur District of Bagmati Prefecture, central Nepal, ~10 km south of the city of Kathmandu.

In Khokana, all buildings collapsed in the 1934 Bihar

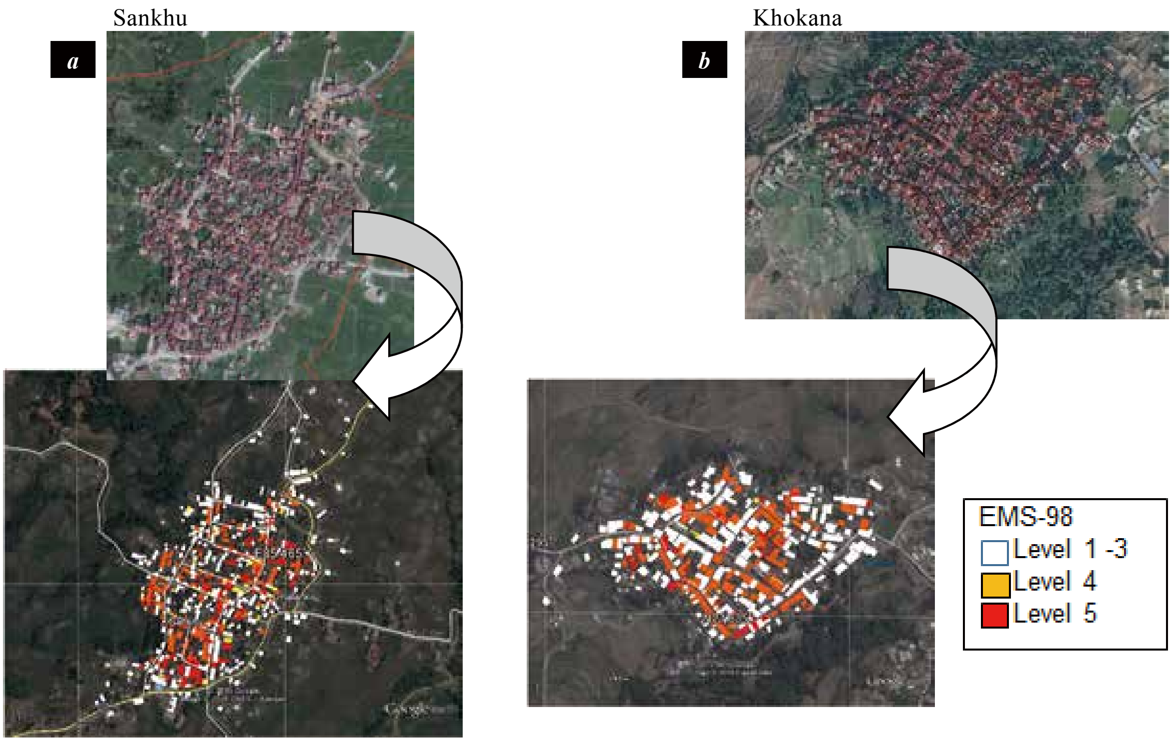


Fig. 7.1 Survey of the damage extent for every house in *a*) Sankhu: (August 17–18, 2015) and *b*) Khokana: (August 19–20, 2015)[5, 6] by the European Macroseismic Scale (EMS) -98.

Table 7.1 Building damage, casualty and census (2010) data for Sankhu.

Damage assesment report for the earthquake on April 25 and aftershock					Censas Report 2010	
ward	Fully damaged	Partially damaged	Dath	Injured	house hold	Population
8	406	65	6	18	378	1779
9	332	61	5	6	279	1306
10	227	97	8	10	317	1370
11	455	68	21	35	353	1732

Shree Shankharpur Municipality, Sanku, Kathmandu, 2015 — Censas Report 2010
Title: Damage assesment report for the earthquake on April 25 and aftershock

Table 7.2 Building damage, casualty and census (2010) data for Khokana.

Damage assesment report for the earthquake on April 25 and aftershock					Censas Report 2010	
ward	Fully damaged	Partially damaged	Dath	Injured	house hold	Population
6	210	32	1	6	241	1277
7	224	60	5	15	307	1746
8	251	49	3	8	285	1503
9	233	26	1	6	267	1527

Karye Binayek Municipality, Khokana, Kathmandu, 2015 — Censas Report 2010

Earthquake, except for one, which is being renovated. Thus, the historical buildings are less than 80 years old. Well-built historical buildings had expensive improvements for earthquake resistance, which included mixing plaster with mud joints.

For the required vulnerability analysis, we recorded building damage, casualty, and census (2010) data from the Karye Binayek municipality office, using transcripts of documents for each ward (**Table 7.2**).

7.3 Survey of damage for every house in Sankhu and Khokana

Damage extent was surveyed for every house in Sankhu on August 17–18, 2015 (**Fig. 7.1*a***) using EMS-98. A high-resolution image from March 12 (before the disaster) was obtained via Google Earth™ prior to the survey. This image was used to identify the position of each building before the earthquake, based on which the extent of damage to each building was estimated in accord with EMS-98.

Khokana was once Newari village and has retained its tradition and culture as a World Heritage Site in Nepal. A damage survey was conducted for every house in Khokana on August 19–20, 2015 (**Fig. 7.1*b***).

We performed a helicopter (chartered through a local supplier) and unmanned aerial vehicle (UAV) photogrammetry survey in Sankhu and Khokana, to map buildings and damage related to the 2015 Nepal Earthquake. NIED and NSET Nepal will use the data for research on building damage distribution, calibration of satellite imagery by ground truth data, and more detailed risk assessment of cities and rural communities as a survey in addition to the ground truth survey.

3D digital surface models of buildings will be created to measure building heights and shapes. Raw photos with oblique views can be used to investigate damage in more detail and structures. This technique was applied to the helicopter and UAV investigation. The helicopter flight was used for a photogrammetry survey of Sankhu on August 20, 2015 (**Fig. 7.2**). We used a helicopter (Bell Jet Ranger 206B) of Fishtail Air Pvt. Ltd (http://www.fishtailair.com/bell-jetranger-helicopter.php) to take aerial photographs.

The UAV flight was used for a photogrammetry survey of Khokana on November 23, 2015 (**Fig. 7.3**). We used a compact UAV, a battery-powered aircraft with onboard digital camera in auto-pilot mode to take aerial photos from 50–150 m above ground. The craft cruises at a speed ~60 km/h for about 20 minutes, covering an area of two square kilometers in one flight. Pictures are processed by photogrammetry software to create Orthomosaic photos for mapping. Safety of the flights and compliance with regulations were of primary importance. Our fixed-wing foam aircraft is much safer than popular multi-rotor drones. It will not injure people if it crashes because: 1) the fuselage is made of soft Styrofoam; 2) the propeller is rear-facing; and 3) it can glide when falling. Autopilot flight can be programmed to avoid prohibited

Fig.7.2 3D digital surface models of buildings using PhotoScan™ for Sankhu. Blue rectangles show camera positions and orientations determined by PhotoScan™.

zones and is above the height limit directed by the Civil Aviation Authority.

Fig. 7.5*a* and ***b*** show the survey of building type classification for every house in Sankhu and Khokana. The number for damage extent of each building type for every house is shown in **Table 7.3** and **7.4**. The difference in damage by building type was remarkable. Damage in Sankhu was extensive. Brick and cement mortar houses without RC columns experienced substantial damage. In contrast, damage to RC structures, particularly those erected in recent years, was generally minor.

The total number of buildings for each area are shown in the upper stage, and the percentages of each item are shown in the lower stage. There was no damage to 94 % of the surveyed RC buildings. From the comparison of BM and BC, the collapse ratio was improved by 16 % in Sankhu and 47% in Khokana for BC houses. There was 0 % BC with very heavy structural damage in both areas.

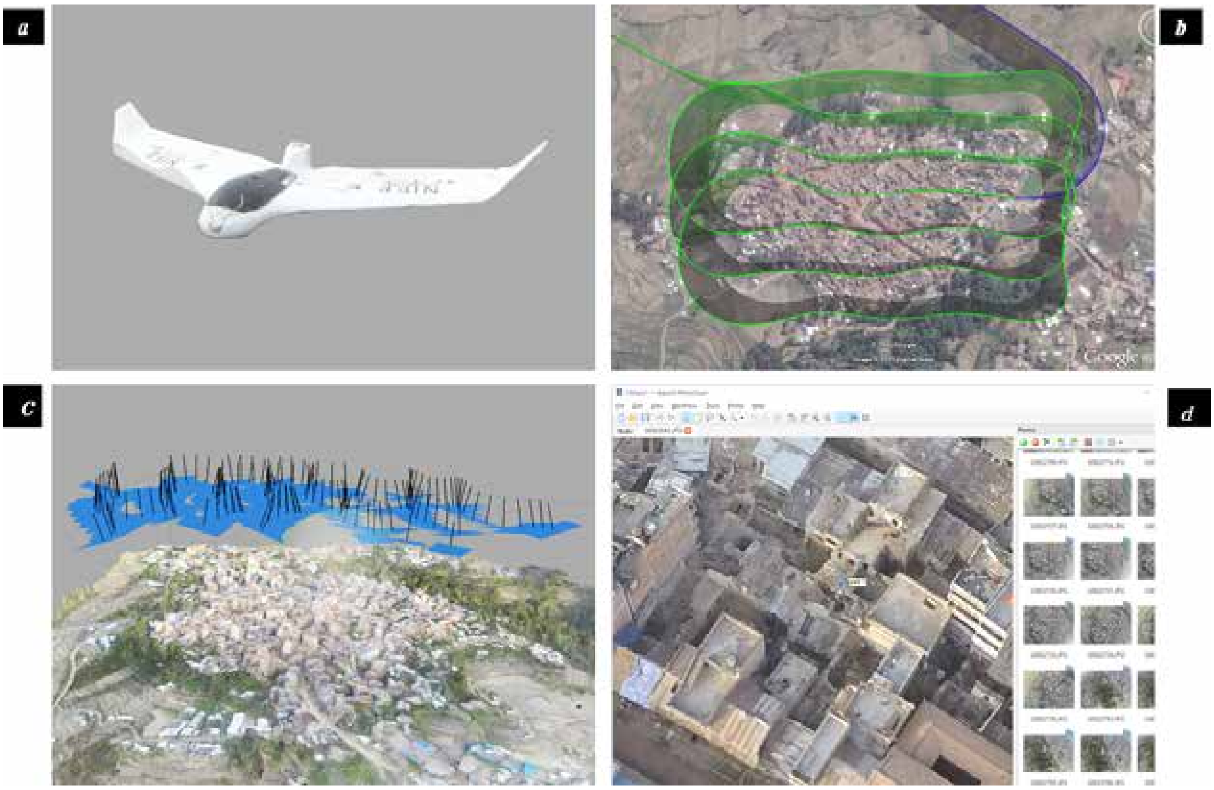


Fig. 7.3 Building damage survey using compact UAV over Khokana.
a: Compact fixed-wing UAV
b: Flight route over Khokana core area
c: 3D digital surface models of buildings using PhotoScan™
d: Building damage survey of every house using PhotoScan™

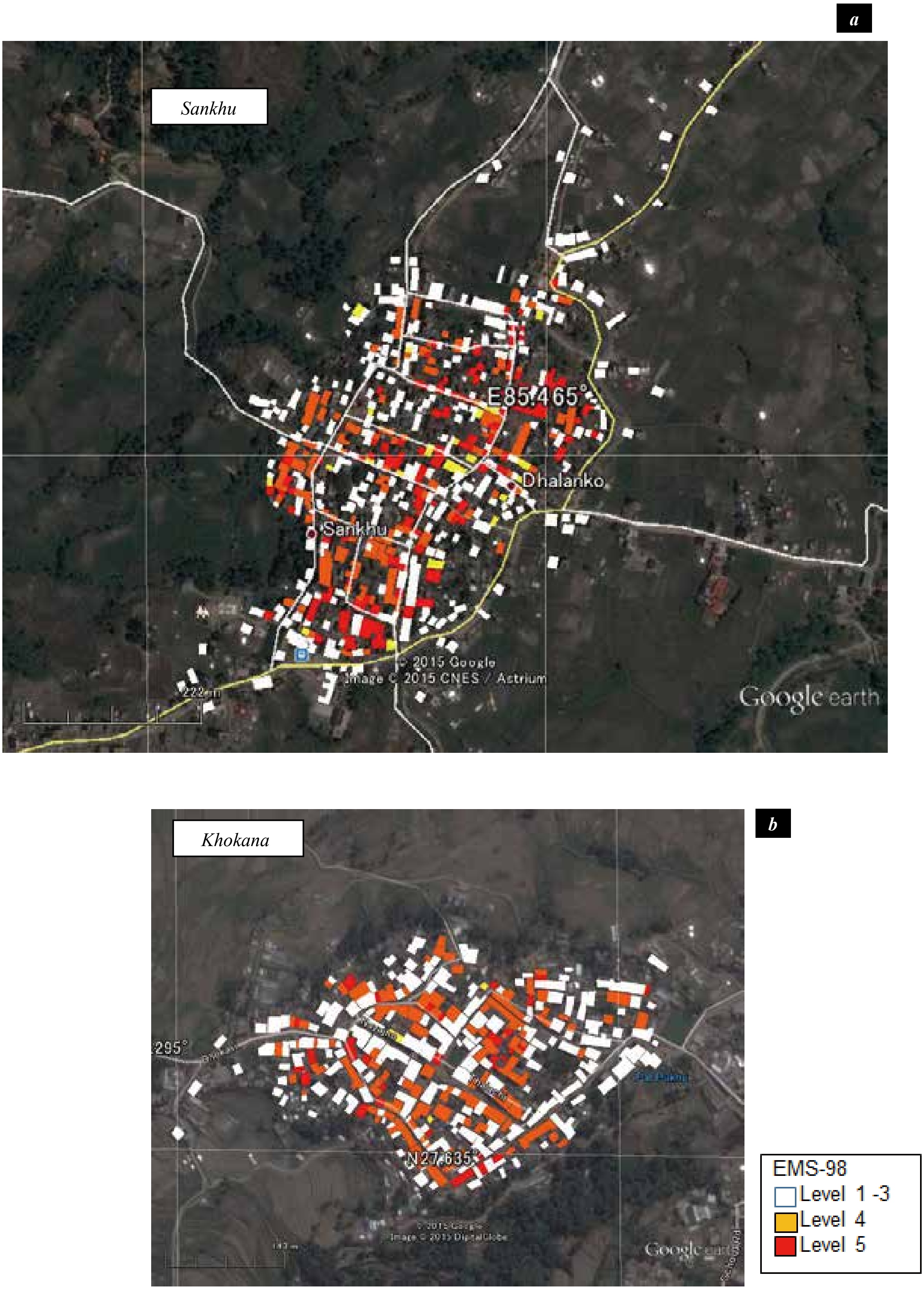


Fig. 7.4 Survey of damage extent for every house in Sankhu and Khokana [5), 6)].

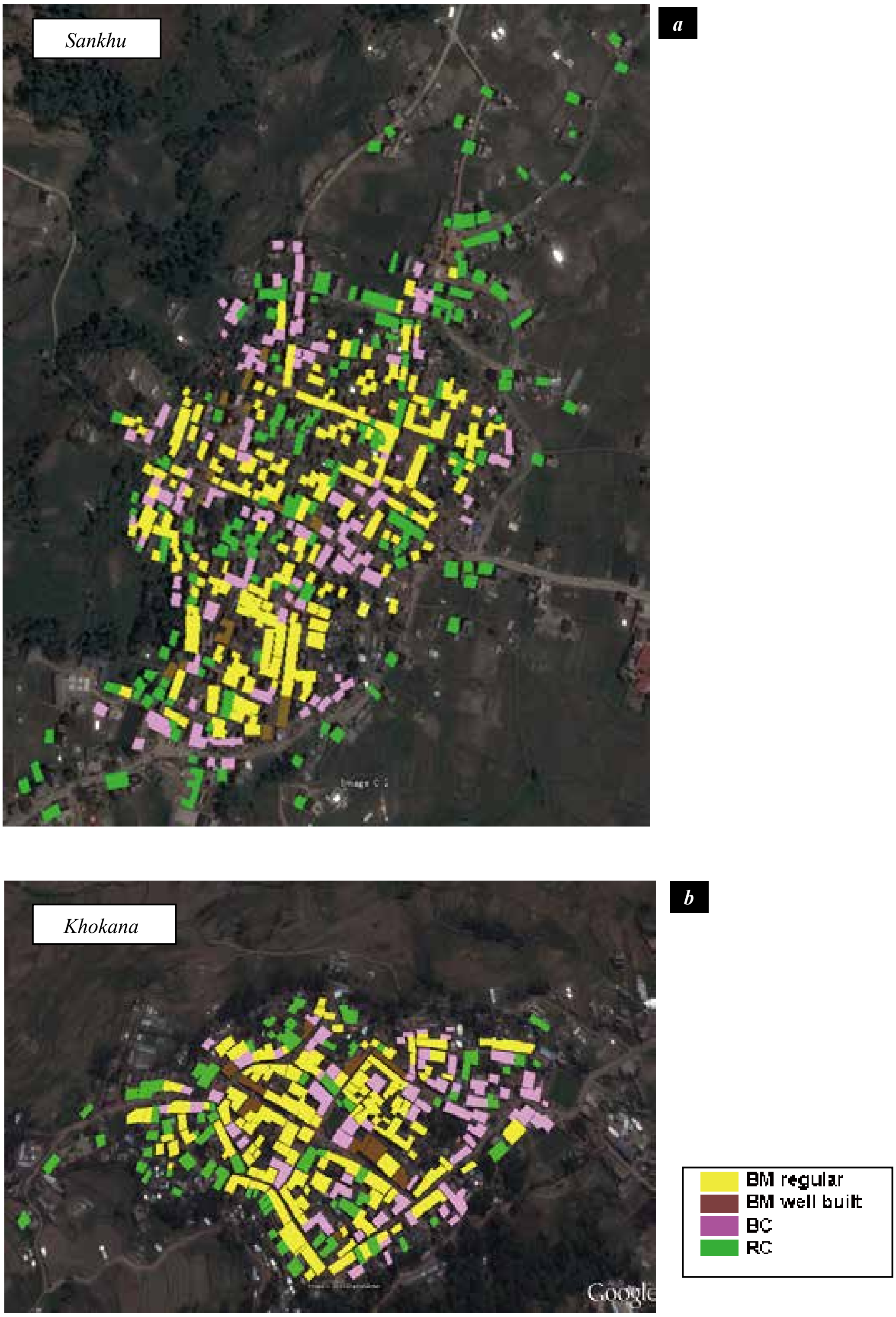


Fig. 7.5 Survey of building type for every house in Sankhu and Khokana.

Table 7.3 EMS level for each ratio and building type in Sankhu.

	EMS-Level 1	EMS-Level 2-3	EMS-Level 4	EMS-Level 5
RC	144	1	9	0
%	94%	0%	6%	0%
BC	76	5	23	15
%	64%	4%	19%	13%
BM Well	9	3	2	0
%	64%	22%	14%	0%
BM	50	13	71	90
%	22%	6%	32%	40%

Table 7.4 EMS level for each ratio and building type in Khokana.

	EMS-Level 1	EMS-Level 2-3	EMS-Level 4	EMS-Level 5
RC	67	0	4	0
%	94%	0%	6%	0%
BC	54	0	17	2
%	74%	0%	23%	3%
BM Well	7	0	4	0
%	64%	0%	36%	0%
BM	39	3	75	28
%	27%	2%	52%	19%

7.4 Core area historical background in Sankhu and Khokana

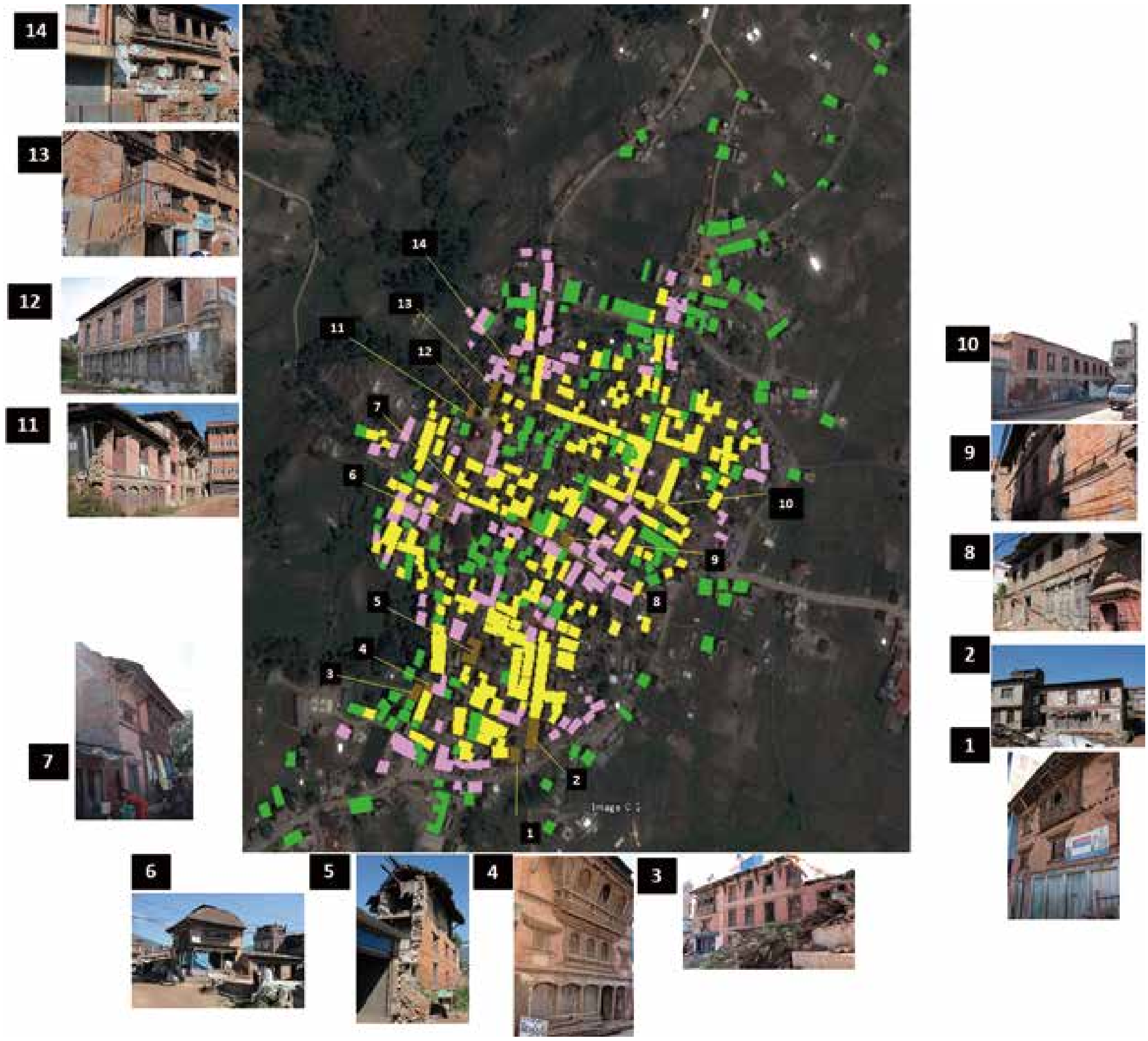
There was heavy structural damage related to the 1934 Bihar Earthquake in both areas. After that earthquake, housing was rebuilt using BM. Well-built historical buildings had expensive renovations; *i.e.*, BMWs were improved by mixing plaster with mud joints. Some BMWs remain in Sanhku (**Fig. 7.6**), and all buildings in Khokana (**Fig. 7.7**) were demolished after the 1934 Earthquake.

Although mud mortar masonry BM buildings remain at the center of the core areas, the high-moisture mud mortar causes less stiffness and the timber floor/roof reduces horizontal strength. There is a problem of earthquake resistance. BM buildings less than two stories are at risk during a large earthquake, and buildings with more than three stories have greater risk. Regarding cement mortar masonry, BC buildings were constructed around 1970–1980 in nearly the entire Kathmandu Valley. This kind of building originated from a lack of construction capacity and technical considerations; for example, they had fewer walls and timbered floors, roofs and brick walls. There remains a problem of reduced horizontal stiffness. RC buildings were first built in 1970. RC columns avoid cracks at corners, and walls can be made from stacked thin bricks. A comfortable living space can thereby be achieved. RC is used widely in housing.

A building is divided by inheritance in a family as a gift to an heir who has a legal right to the estate. In Nepal, such buildings have a complicated structure because of this custom of succession, with BM, BC and RC. An identical building is partitioned between the families. The number of houses of this grand truth investigation is of little value from the census (2010) data. This is apparent from the outward appearance.

7.5 Completion with fragility curves

JICA (2002) study [1), 2) 3)] defining fragility curves for estimating damage to buildings was to determine the relationship between damage ratio and ground acceleration for each building type. These curves refer to the graph showing this relationship. In this study, the curves for



1	: Constructed in about 140 years ago.
2	: Constructed in about 140 years ago.
3	: Constructed in about 100 years ago.
4	: Constructed in about 100 years ago.
5	: Constructed in about 275 years ago.
6	: Constructed in about 100 years ago.
7	: Constructed in about 100 years ago.
8	: Constructed in about 100 years ago.
9	: Constructed in about 70 years ago.
10	: Constructed in about 150 years ago.
11	: Constructed in about 100 years ago.
12	: Constructed in about 100 years ago.
13	: Constructed in about 100 years ago.
14	: Constructed in about 100 years ago.

Fig.7.6 Survey of well build houses in Sankhu.

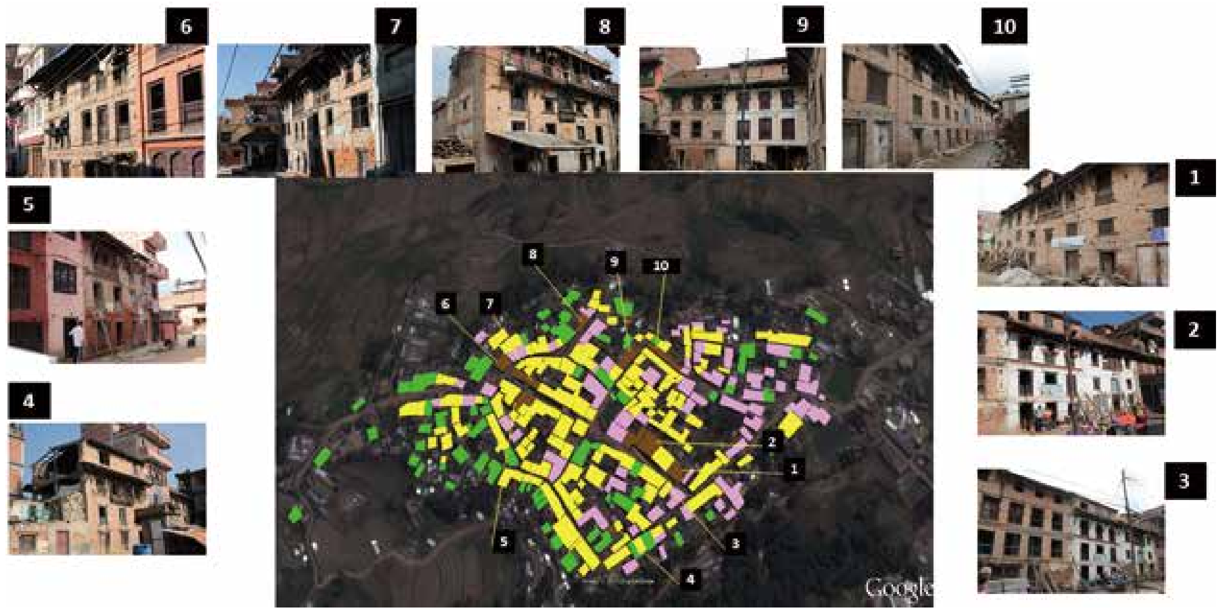


Fig. 7.7 Survey of well build houses in Khokana.

buildings in the Kathmandu Valley were determined as shown in **Fig. 7.8*a*** and ***b***.

In the aforementioned JICA study, fragility curves for buildings in the valley were adjusted by calibrating existing fragility curves for Indian buildings from Arya (2000)[7] and those for West Nepal from a UNDP/UNCHS (1994) study[8]. For this calibration, damage from the 1988 Udayapur earthquake cited in Murakami *et al.* (1990)[9] and Dikshit (1991)[10] were analyzed. These papers present very large seismic intensity distributions compared to the expected peak ground accelerations. We reanalyzed the intensity considering building weakness in our damage area, most of which are AD or poor BM. Fragility curves of the relationship between damage rate and peak ground acceleration for each building type are shown in **Fig. 7.9**.

In the 2015 Gorkha Earthquake, there were no acceleration observation points in Sankhu and Khokana. The USGS maximum acceleration record was 160 Gal at the US embassy in the city of Kathmandu. According to Tkani *et al.* (2015)[11], the main shock in the observation results was 151 Gal at Lalitpur and 146 Gal at Thimi. Estimation of main shock acceleration values was 150 Gal in Sankhu and Khokana.

Damage ratio of RC is 7-8 % and damage ratio of BM is the 80 %.

Graed 5, damage ratio of RC is 0 %, damage ratio of BM is 40%. In Khokana, damage ratio (**Table 7.5**) of RC is 6 %, BM is 70 %. Collapse ratio of RC is 0 %, BM is 20 %. The damage curved line of BM is exceeded the damage curved line of ST, AD.

BM is composite structure including the sun-dried brick (AD). The building classification is different in ages and referred earthquakes (*i.e.*, the 1934 Bihal Earthquake, the 1988 Udayapur Earthquake).

Fig. 7.9 shows story height development (Scheibler, G., 1988)[12]. The building 1st floor could be built by a sun-dried brick in is enlarged specifically. According to this figure, building is the development of the number of floors outlined, and the simultaneous horizontal compression which runs parallel to it from a single-element to a double-element construction.

The complicated composite structure is being classified in BM by the damage function. On the other hand, RC is actual damage rate and the damage function rate are good agreement (**Table 7.5**).

Table 7.5 Fragility curves (JICA, 2002)[1), 3)] and damage and collapse rate.

		damage rate		collapse rate	
		RC(%)	BM(%)	RC(%)	BM(%)
Fragility curves	Estimation	7-8	20	5	17
Sankhu	Real damage	6	72	0	40
Khokana	Real damage	6	71	0	19

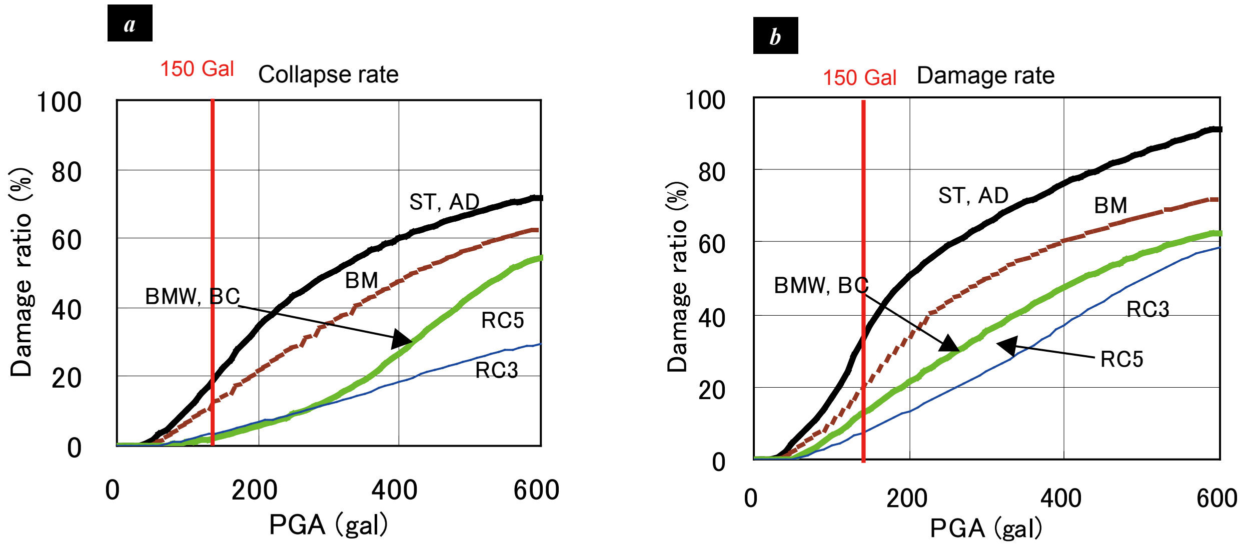


Fig. 7.8 Fragility curves of relation between damage rate and peak ground acceleration.

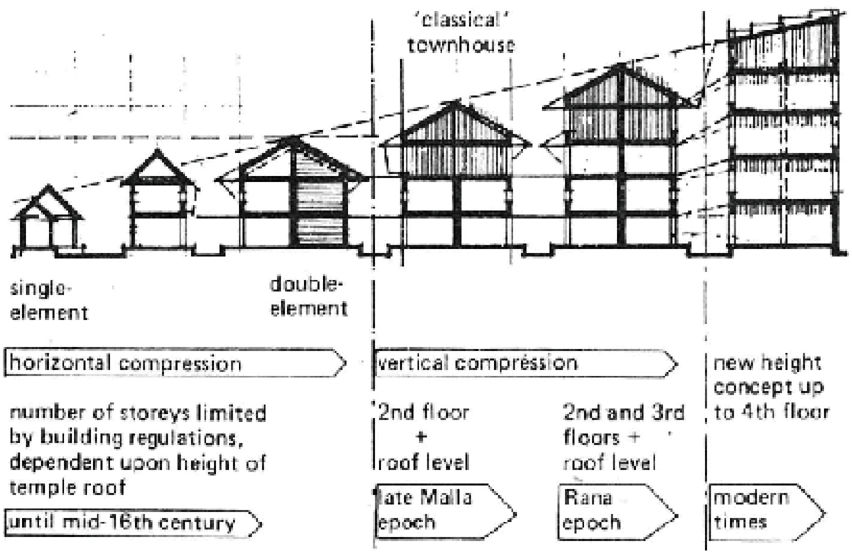


Fig. 7.9 Story height development (Scheibler, G., 1988)[12].

7.6 SAR analysis

In the severely damaged core area, the principal mechanism of microwave radar backscattering changes from double-bounce to rough-surface scattering (**Fig. 7.10**). This change corresponds to a decrease of coherence (γ) in synthetic aperture radar (SAR) imagery observed before and after the disaster (**Fig. 7.11**). The value of γ represents the similarity between two images. A decrease in γ was determined in the data obtained over Sankhu and Khokana by the Japanese SAR satellite ALOS-2, and this was used to delineate severely damaged urban areas. Field surveys confirmed that damaged areas were effectively detected by a decrease in γ (Watanabe *et al.*, 2015)[6].

Fig. 7.12 shows the full view area as a Google Earth image, including (*a*) the Timi, Bhaktapur and Sankhu core areas, and (*b*) the Kirtipur, Khokana and Bungamati core areas. The damaged core area is identified using the coherence change ($\Delta\gamma$) obtained before the disaster (γ_{pre}) and between the disasters (γ_{int}).

Fig. 7.13 shows regions of bright reflections within severely damaged core areas such as Timi, Bhaktapur and Sankhu. **Fig. 7.14** shows the coherence magnitude and a survey of damage extent for every house in Sankhu. The decrease in coherence (γ) in the SAR imagery observed before and after the disaster readily facilitated detection of damage in the region.

Fig. 7.15 shows regions of bright reflections within severely damaged core areas such as Khokana and Bungamati. **Fig. 7.16** shows the coherence magnitude and a survey of damage extent for every house in Khokana. Reflections in the slightly damaged Kirtipur core area are not as clear and bright as those in the severely damaged core areas of Khokana and Bungamati.

Why was there only slight damage at Kirtipur?

The epicentral distance of the Kirtipur core area was 79.74 km, compared with 80.69 km for the epicentral distance of the Khokana core area. Both core areas are old traditional towns on small hills in the southwestern Kathmandu Valley (**Fig. 7.17**, **18**). According to Takai *et al.* (2015), acceleration was amplified in Patan (Khokana) located in the Kathmandu Valley. In contrast, acceleration was less amplified in Kirtipur, which is located on outcropping basement rock units outside the valley (**Fig. 7.19**).

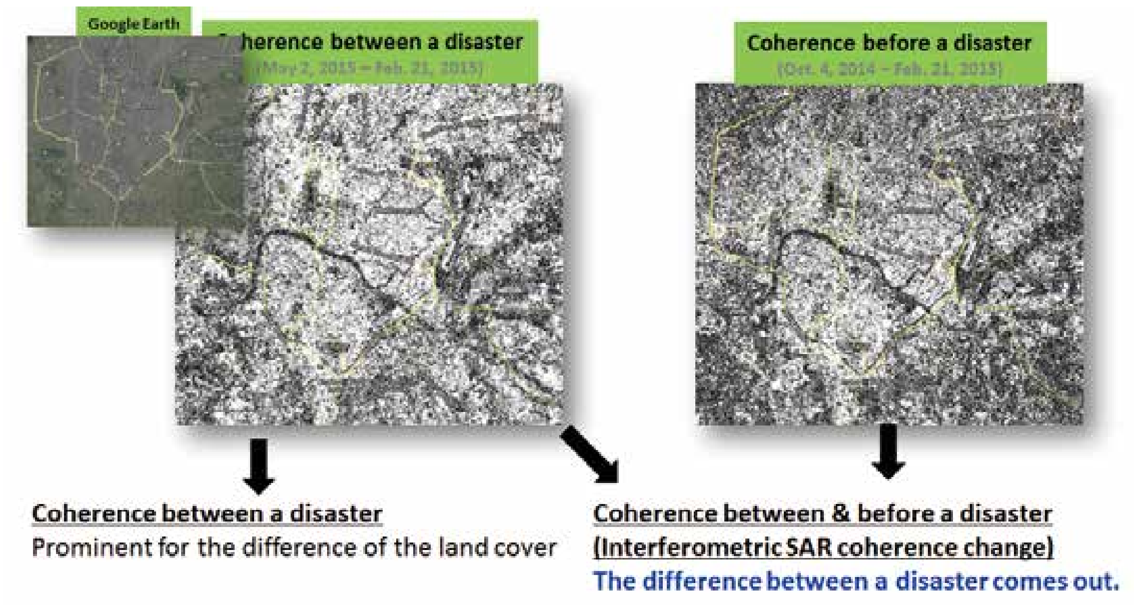


Fig. 7.10 Illustration of interferometric SAR coherence change.

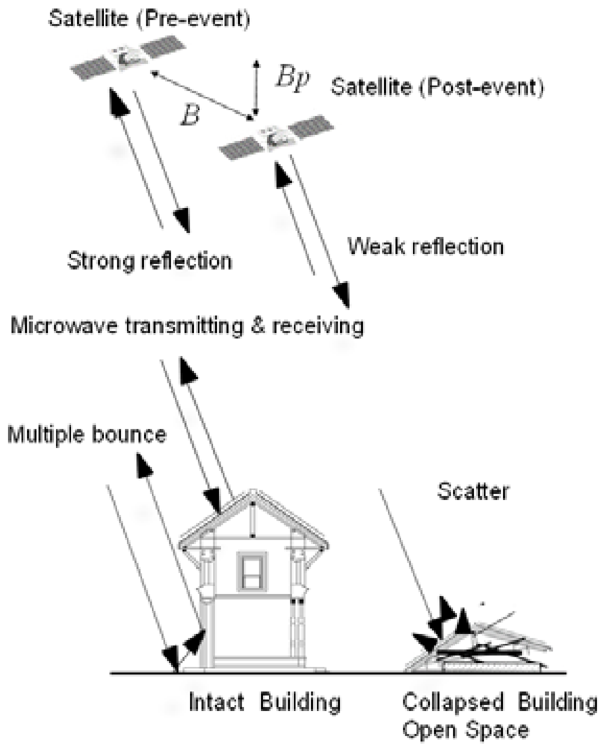
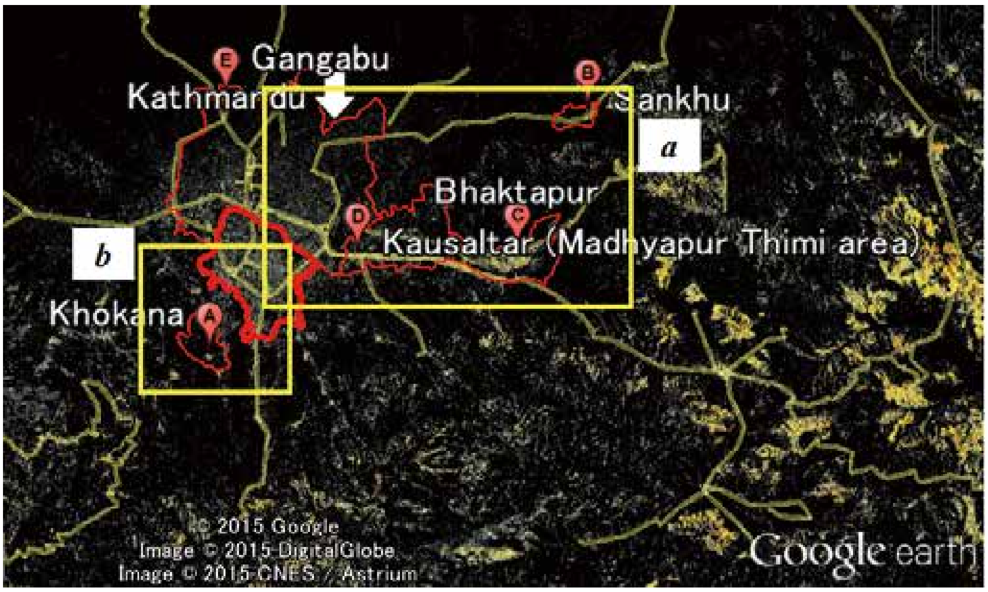


Fig. 7.11 Whole interferogram obtained by the analysis.



$$\Delta\gamma = \frac{\gamma_{pre2-pre1} - \gamma_{pre2-int}}{\gamma_{pre2-pre1} + \gamma_{pre2-int}}$$

Red : Δγ ≥ 0.4
Orange : Δγ ≥ 0.3
Yellow : Δγ ≥ 0.2

Fig. 7.12 Full view of the area as a Google Earth image, including (a) the Timi, Bhaktapur and Sankhu core areas and (b) the Kirtipur, Khokana and Bungamati core areas.
The damaged core area is detected using the coherence change ($\Delta\gamma$) obtained before the disaster (γ_{pre}) and between the disasters (γ_{int}).
Subscript (pre2-pre1): Two coherences that were acquired from the images before the disaster (γ_{pre}).
Subscript (pre2-int): Two coherences that were acquired from the images before the disaster (γ_{pre}) and between the disasters (γ_{int}).

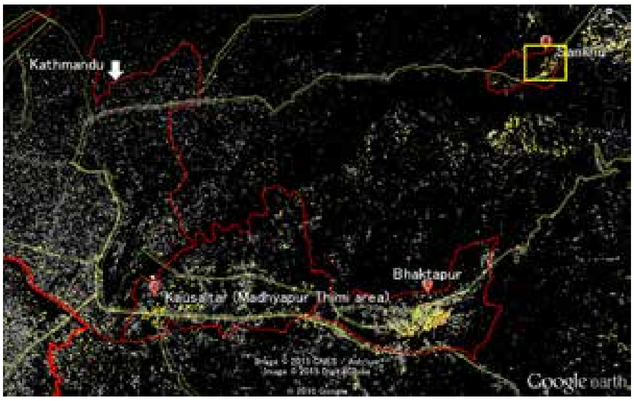


Fig. 7.13 Bright reflection areas for severely damaged urban area such as Timi, Bhaktapur and Sankhu core areas.

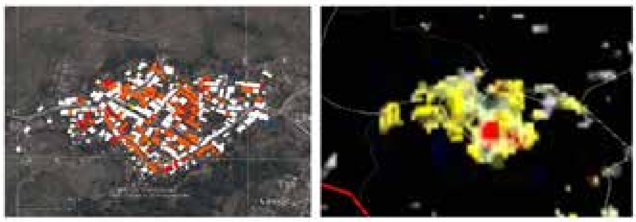


Fig. 7.14 Coherence magnitude and the survey of damage extent for every house in Sankhu.

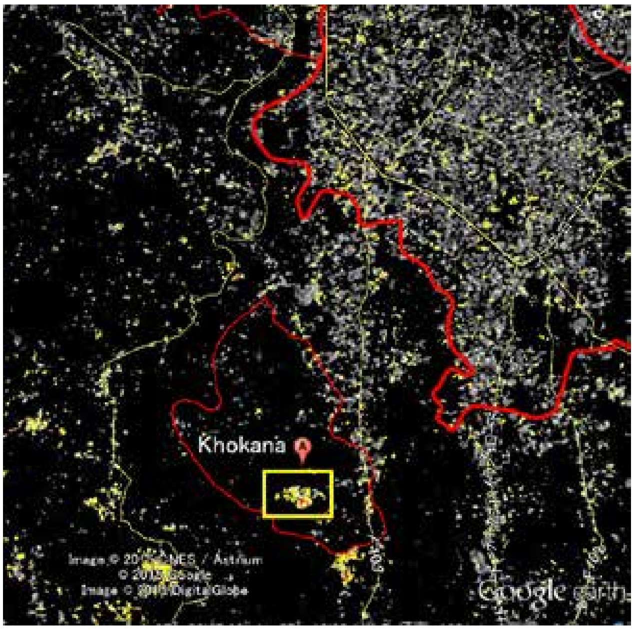


Fig. 7.15 Bright reflection areas for Khokana and Bungamati core areas. Kirtipur was not clear bright reflection.

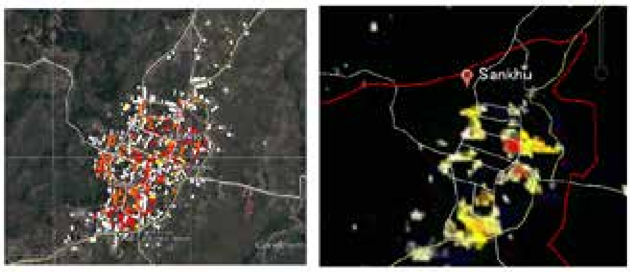


Fig. 7.16 Coherence magnitude and survey of damage extent for every house in Khokana.

Fig. 7.17 The Kirtipur core area is located on small hills (photo by T. Ohsumi).

Fig. 7.18 The Khokana core area is located on small hills (photo by T. Ohsumi).

Fig. 7.19 Outcropping basement rock in Kirtipur (photo by T. Ohsumi).

8. After the 2015 Gorkha, Nepal Earthquake and beyond

The recovery and reconstruction processes following the 2015 Gorkha, Nepal Earthquake are ongoing. The damage to reinforced concrete (RC) structures was generally minor. Many of the non-engineered masonry structures that experienced complete collapse or partial damage were two- to four-story buildings. Although many of the masonry structures will be reconstructed as RC structures, traditional building methods should be sustained by traditional communities not only to conserve world heritage but also to improve the earthquake resistance of cities. In the following paragraphs we present a method for the constructing earthquake-resistant buildings using traditional methods.

8.1 Stabilized mud mortar with lime

In the Sankhu core area, traditional buildings over 100 years old suffered little damage in the 2015 Gorkha Earthquake. Well-built historical buildings underwent expensive improvements for earthquake resistance, which included using a mix of plaster and mud. Rashmi *et al.* (2014) proposed the use of a homogenous mixture comprising fine aggregates as mud mortars to bind, individually or combined with cement and lime (**Fig. 8.1**). The workability and strength of twelve different combinations of stabilized mud mortars were examined. The compressive strength of mortar with 50 % sand and 12 % cement is in the range of 4.25 MPa, which is within the IS (Indian Standard) code specification. The use of this mixture as a stabilizing mud mortar in construction was shown to be sustainable as well as economical.

Rashmi, S., Jagadish, K. S., Nethravathi, S., 2014, Stabilized mud mortar, *International Journal of Research in Engineering and Technology*, Vol. 03, Special Issue: 06, eISSN: 2319-1163, pISSN: 2321-7308.

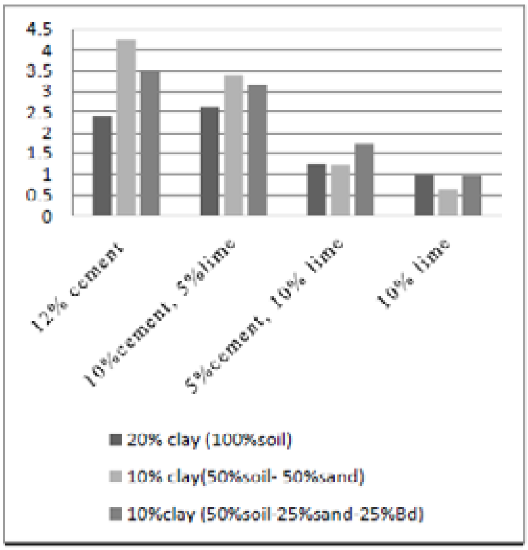


Fig. 8.1 Compressive strength of various mortar mixtures measured over 28 days (Rashmi *et al.*, 2014).

8.2 Horizontal timber beam reinforcement

A number of documents discussing improvements in seismic-resistant construction methods for masonry structure were prepared under the National Building Code Development Project (NEP/88/054/21.03) in 1993.

“Guidelines for Earthquake Resistant Building Construction: Low Strength Masonry (LSM)” is one of them. This document provides basic guidelines for earthquake-resistant construction methods of low-strength masonry.

NBC 202: Mandatory Basic Rules for Load Bearing Masonry

NBC 203: Guidelines for Earthquake Resistant Building Construction: Low Strength Masonry

NBC 204: Guidelines for Earthquake Resistant Building Construction: Earthen Buildings (EB)

NBC 203 and 204 describe the effect of wooden strips as horizontal reinforcing members. Timber strips can be applied in a similar manner to the Naga pasa ('snake mating tie'; **Fig. 8.2**). An assemblage of two parallel lengths of timber connected by struts is placed horizontally in the wall covering the entire thickness of the wall, as illustrated in **Fig. 8.3**.

Fig. 8.2 Masonry building with a Naga pasa.

In Dolakaha Bazaar, an old town located 4 km from Charikot in north-eastern Nepal, buildings installed horizontal timber support planks. The timber planks were installed between the first and second floors of the building, along the outside wall of the building. In buildings with narrow sides and a gable wall, the timber is usually fitted along the outer periphery of the building separate from the floor beam. In the long side of the building, the timber is installed so as to form a common joint in the outer periphery of the building. The corner joint varies according to the building style, but notched joints are commonly used (**Fig.s 8.4, 8.5**).

Traditional construction methods should be sustained by traditional communities not only to conserve world heritage but also to improve the earthquake resistance of cities. Technologies for the construction of earthquake-resistant buildings using traditional methods such as stabilizing buildings using mud mortar with lime and horizontal timber beams are both effective and sustainable.

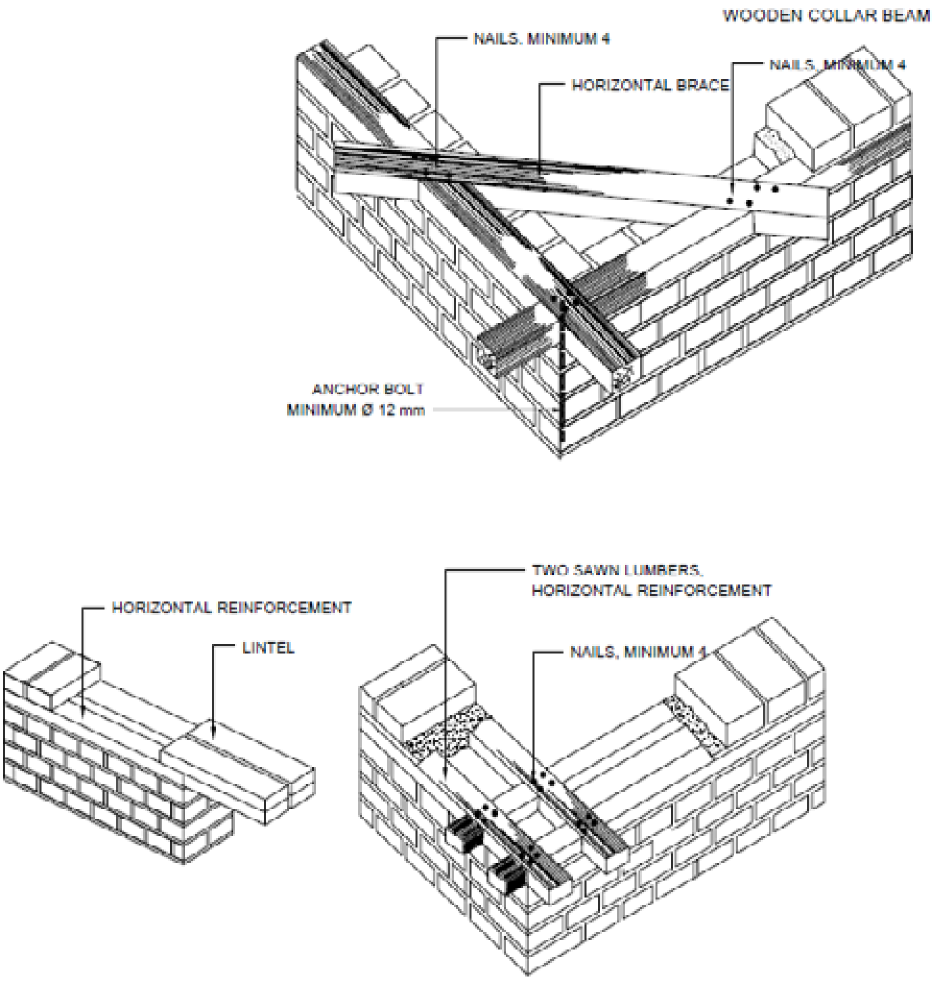


Fig. 8.3 Placement of timber for horizontal reinforcement bands (after National Building Code: NBC203).

Fig 8.4 Timber band installed between the first and second floors in a house in Charikot.

Fig 8.5 Corner joint of horizontal timber planks (photos by H. Imai).

9. Finding

1) RC buildings were partially damaged, and many masonry buildings were severely damaged. The difference in damage extent between the various building types was remarkable.
2) BM buildings remain in urban and rural areas. These buildings have very poor horizontal rigidity because of low bond strength and strong moisture absorption in mud joints, wooden floors and roofs.
3) Damage extent and building type classification were surveyed for every house in Sankhu and Khokana. There was no damage to 94 % of surveyed RC buildings. The collapse ratio was improved using BC relative to BW.
4) Some buildings survived the 1934 Bihar Earthquake, as did some during the 2015 Gorkha Earthquake in Sankhu. These building structure types were classified as well built, using a type of brick with mud mortar.
5) For RC, the actual damage rate and damage function rate were in good agreement. The damage curve of BM exceeded that of ST and AD.
6) Tradition *chowks* are observed to have excellent earthquake resistance. However, *chowks* that have been altered and/or changed were damaged.
7) Comparison of the coherence magnitude with a survey of the damage extent for every house in Sankhu and Khokana detected damage well. Greatest damage correlated with the decreases of coherence (γ) in SAR imagery observed before and after the disaster. The brightest reflections occurred for severely damaged core areas, such as those in Khokana and Bungamati. Regions of less-bright reflections, such as those observed in Kirtipur, corresponded to only slightly damaged core areas.
8) Traditional construction methods (*i.e.* stabilizing buildings using mud mortar with lime and horizontal timber beams) should be sustained by traditional communities not only to conserve world heritage but also to improve the earthquake resistance of cities.

Nepal and Japan have a long history of cooperation in earthquake engineering. Many joint research projects have been carried out in the academic field for earthquake disaster mitigation. The year 2016 marks the 60th anniversary of the establishment of diplomatic relations between Nepal and Japan. All members of the NIED and JAXA team wish to strengthen the partnership in earthquake engineering that has been developed between the two countries through ongoing cooperation in investigations of the subject earthquake disaster and future joint research projects. We hope that, in Nepal, greater affordability of earthquake-resistant technology may help it to become widespread.

Acknowledgments

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2015 年 4 月ネパール地震 (Gorkha 地震) における地震の概要と建物被害に関する情報収集調査報告

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要　旨

2015 年 4 月 25 日 11 時 56 分 (現地時間)，ネパール中北部を震源域とするマグニチュード (M_w) 7.8 の地震が発生した．首都カトマンズを中心とする広い領域で，主としてレンガ組積造建物が倒壊による多くの被害が発生した．

防災科学技術研究所 (NIED) は被害調査チームを組織し，第 1 次調査 (5 月 26 日から 6 月 3 日)，第 2 次調査(6 月 17 日から 24 日), 第 3 次調査(8 月 16 日から 21 日), 第 4 次調査(10 月 27 日から 11 月 2 日) を実施し，現地調査および情報収集を行った．

Chapter 1 では，この 1 次・2 次調査で実施した地震ハザード・リスク評価，地震被害推定手法の研究として，現地の煉瓦組積造及び石造りの建物調査を実施した．建物調査の 1 次調査により，調査地域を選定した．また，ネパールで観測された本震・余震の USGS の調査結果を示した．

Chapter 2 では 3 次・4 次調査で実施した選定された地点(サクーとコカナの旧市街)の全棟被害調査を実施した．主たる目的としては，防災科研と JAXA が進めている衛星データからの被害想定のためのクランド･ツルースの利活用に関する研究の成果を活用し，今後の詳細建物調査につなげるものである．対象はサクーとコカナとし，EMS-98 に基づいて建物被害の全棟調査を実施した．

キーワード：コルカ・ネパール地震，カトマンズ，煉瓦組積造，石造り，グランド・ツルース