

Research Paper

The 2015 Nepal Gorkha Earthquake: An overview of the damage, lessons learned and challenges

H. Hazarika¹, N.P. Bhandary², Y. Kajita³, K. Kasama⁴, K. Tsukahara⁵ and R.K. Pokharel⁶

ARTICLE INFORMATION

Article history:

Received: 23 July, 2016

Received in revised form: 01 September, 2016

Accepted: 03 September, 2016

Publish on: 30 September, 2016

Keywords:

2015 Nepal earthquake

Amplification of motion

World heritages

Landslide

Compound disaster

ABSTRACT

This paper describes the damage brought by the 2015 Nepal earthquake to urban infrastructures, modern and traditional buildings as well as some world heritage sites in and around Kathmandu city. The paper also focuses on a disaster brought to a hydropower plant by the compound action of a previous landslide and this time earthquake. Some of the possible reasons for such damage were brought to light, and challenges of the geotechnical community towards the retrofitting and recovery of the devastated structures were discussed.

1. Introduction

The Nepal Gorkha earthquake (moment magnitude, $M_w=7.8$) struck at 11:56 NST on 25 April 2015 with epicenter at Barpak village of Gorkha district, which is located 77 km northwest of Kathmandu, the capital city of Nepal (**Fig. 1**). This was the largest earthquake in Nepal's history since 1934 Bihar–Nepal Earthquake. The re-cent report by the Government of Nepal indicates that the recorded death toll has reached close to 9,000. Immediately after the earthquake a Japanese expert team from three professional societies was sent for quick survey of the damage area. The professional societies were: the Japanese Geotechnical Society (JGS), Asian Technical Committee of ISSMGE on Geotechnical Natural Hazards (ATC3), Japan Society of Civil

Engineers (JSCE) and Japan Association for Earthquake Engineering (JAEE).

The first author and the second author were a part of the JGS team, and surveyed some areas in and around the city of Kathmandu. Also, Kyushu University dispatched a survey team (consisting of the co-authors of this papers) to Nepal in August 2015, in order to assess the situation aftermath of the earthquake and help the post-earthquake recovery and reconstruction of Nepal.

This paper summarizes the damage brought by the devastating earthquake especially to urban infrastructures, the historical monuments, modern and traditional buildings as well as some world heritage sites in and around Kathmandu city. The paper also focuses on a compound disaster brought to a hydropower plant by a previous landslide and subsequently by the earthquake. Finally, the paper also divulges possible

¹ Professor, Department of Civil Engineering, Kyushu University, Fukuoka, JAPAN, hazarika@civil.kyushu-u.ac.jp

² Associate Professor, Graduate School of Science and Engineering, Ehime University, Matsuyama, JAPAN, netra@ehime-u.ac.jp

³ Associate Professor, Department of Civil Engineering, Kyushu University, Fukuoka, JAPAN, ykajita@doc.kyushu-u.ac.jp

⁴ Associate Professor, Department of Civil Engineering, Kyushu University, Fukuoka, JAPAN, kasama@civil.kyushu-u.ac.jp

⁵ Professor, Department of Urban and Environmental Engineering, Kyushu University, Fukuoka, JAPAN, tsukahar@doc.kyushu-u.ac.jp

⁶ Professor, Graduate School of Information Science and Electrical Engineering, Kyushu University, Fukuoka, JAPAN, pokharel@ed.kyushu-u.ac.jp

Note: Discussion on this paper is open until March 2017

reasons for such damage and geotechnical challenges towards the retrofitting of structures and reconstructions of the devastated areas.

2. Tectonics of Kathmandu Valley and mechanism of earthquake

2.1 Past earthquakes in Nepal

The record of historical earthquakes in the Ne-pal Himalaya dates back to the 13th century, but no clear documentation of the damage that occurred is available in the literature. Tabulated data on the historical earthquakes in Nepal and peripheral areas, as compiled by NSET and GHI (1999), indicate that a large earthquake occurs in the Nepal Himalaya roughly every 100 years. Since the last large earthquake in 1934 (i.e., Bihar–Nepal Earth-quake, M8.1), 81 years have passed and it was widely estimated that a large earthquake was going to occur in the Nepal Himalaya within 100 years from 1934. During the last 35 years, three heavily damaging earth-quakes and several dam-aging earthquakes have struck Nepal. The heavily damaging earth-quakes include the 1980 far western region earthquake (M6.5, Darchula), the 1988 eastern Nepal earthquake (M6.5, Udayapur), and the 2011 earthquake (M6.9, Nepal–India border) while damaging earthquakes of <M6.0 were recorded almost every year from 1993 until 2003. In addition, there is a long list of minor earthquakes that occur almost every month in and around the Nepal Himalaya. These earthquake data indicate that Nepal is situated in a highly earthquake-prone plate tectonic zone of the Himalayas.

2.2 Mechanism of the earthquake

The occurrence of earthquakes in the Himalayan region is primarily due to the collision between the Indian plate and the Eurasian plate (sometimes also referred to as the Tibetan plate in local or regional scale). As indicated in **Fig. 2**, the Indian plate moves northward and subducts underneath the Eurasian plate creating a zone of plate-tip squeezing at the Himalayas. This plate movement has resulted in the formation of the Himalayan Mountains, the uplift of which occurs at an estimated rate of 2 cm per year (Bilham et al., 1995). Moreover, the area-wide compression and uplift of the Himalayan region has resulted in extensive distribution of regional and local faults. Some of these faults generate major earthquakes, such as the 2008 Sichuan Earthquake during which nearly 88,000 people died. So far, however, the major earthquakes in and around the Nepal Himalaya have

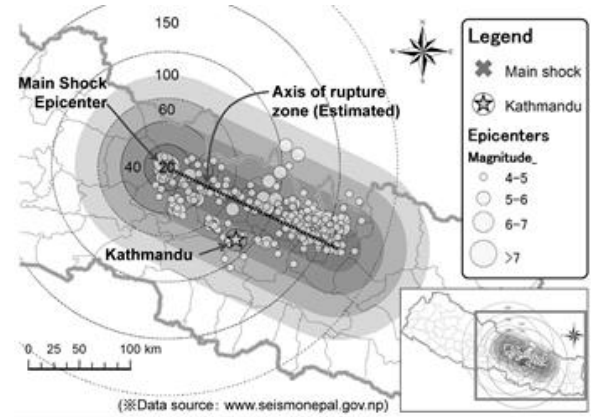


Fig. 1. Epicenter of the earthquake and distribution of aftershocks.

been mostly generated at the subduction zone of the Indian plate underneath the Eurasian plate (**Fig. 2**). The depth of the 2015 Nepal Earth-quake has been estimated to be about 15 km, which makes it clear that this earthquake was generated exactly at the depth of subduction plane. The exact mechanism involved in the generation of this earthquake is yet to be clearly known, but a general interpretation is that the strain energy stored in the rupture zone due to the northward gently inclined thrust of the Indian plate was re-leased with slipping of Eurasian plate-tip below the Main Boundary Thrust (MBT; **Fig. 2**).

Among the most dramatic and visible manifestations of plate-tectonic forces are the lofty Himalayas, where the two large landmasses of India and Eurasia collide as a result of plate movement. Because the rock densities of both of these continental landmasses are roughly the same, one cannot easily subduct under the other. Thus, the Main Himalayan Thrust dips at a relatively low angle (6° - 14°) towards north (Mukhopadhyay, 2014).

3. Damage to urban infrastructures

9.142 km segment of the Kathmandu-Bhaktapur Road section of the Araniko Highway was upgraded by expanding the previous two-lane road to four lanes through JICA (Japan International Cooperation Agency) funded project. The road is also known as Nepal-Japan friendship road. The Kathmandu-Bhaktapur Road is designed to serve not only as a road to ensure smooth transportation of goods and people between Kathmandu and Bhaktapur, but also to link the Kathmandu Valley with the Eastern Terrain via the Araniko Highway and the Sindhuli Road. Furthermore, this road section also improved the connection of the Kathmandu Valley with the north via the Araniko Highway, which is a vital physical infrastructure for Nepal in terms of connectivity

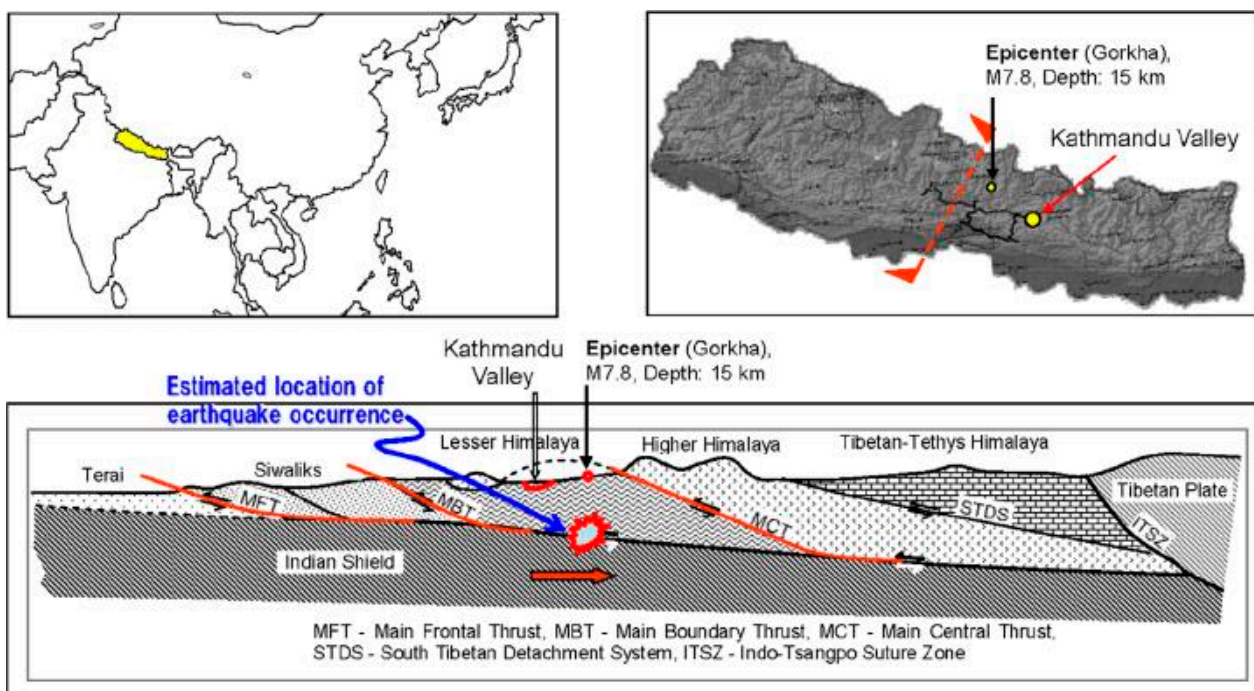


Fig. 2. Mechanism of the earthquake.

to China and India (JICA, 2007). A part of the road was damaged due to the earthquake. This section summarizes the damage of the road and the surrounding infrastructures during the earthquake as well as the geological and geotechnical information available close to the area.

3.1 Damages to the road and surrounding infrastructures

Our survey focused only on the damage of the road located near the Lokanthali area (Fig. 3), covering a length of about 400 m. The state of the road before and after the earthquake (Fig. 4) is shown in NPC (2015a) Post disaster needs assessment, **A: Key findings**. Kathmandu, Nepal: Government of Nepal, National Planning Commission.

The various locations of the surveyed area were are shown in Fig. 5. In the Kathmandu side, heaving and subsidence of the road, slope failures in the main road and in the access road, ground fissuring, retaining wall damage and damage to the residential buildings close to the access road were observed. Similarly, in the Bhaktapur side, heaving and subsidence of the main road, slope failures in the access road and ground fissuring were observed.

Slope failure in location 3 is shown in Fig. 6. As seen in the figure the traffic police box was tilted by about 12 degree due to slope failures and settlement of the road. In the Bhaktapur side (location no. 7) subsidence of the main road was observed (Fig. 7a). Also, slope failure took place in the access road (Fig. 7b). In location 5,

huge settlement of the access road in the Kathmandu side was observed (Fig. 8a). An apartment building close to this sinking road was found to be settled and tilted as seen in Fig. 8(b).

In location 4, two types of retaining walls exist: One is the reinforced retaining wall and the other is the gravity retaining wall. As seen from Fig. 9(a), in the joint between the two walls, damage was observed. Also, in some parts of the gravity retaining wall, cracks were observed along the same line in which ground fissuring of the access road was observed Fig. 9(b). Ground fissuring extended up to the residential areas along the road. Two residential buildings located along this fissure were found to be heavily damaged (Fig. 10). According to the owner the building with exposed brick structure, whom the authors happened to meet, the building settled by about more than 1 m towards the road and tilted. Many ground fissuring were also observed in the surrounding of the two buildings.

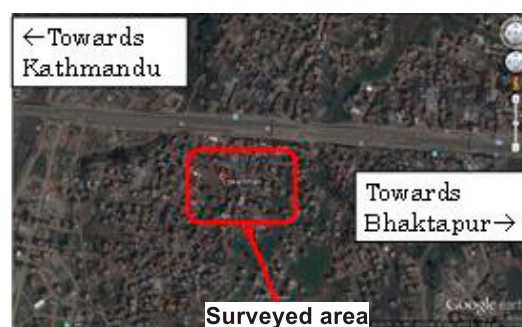


Fig. 3. Kathmandu-Bhaktapur road (URL Source: <http://www.earth.google.com>).

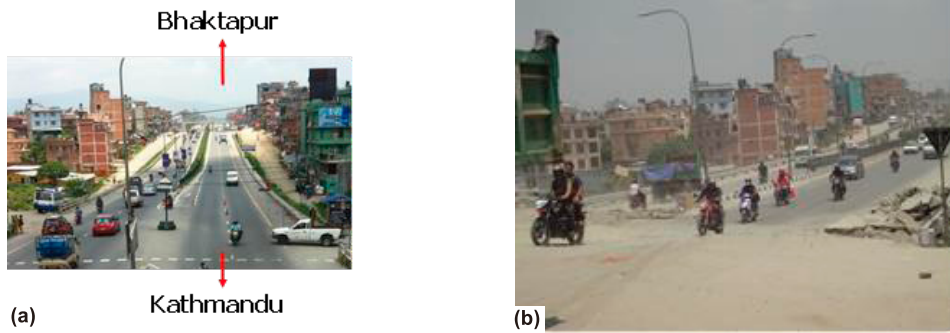


Fig. 4. State of the road (a) before the earthquake and (b) after the earthquake.

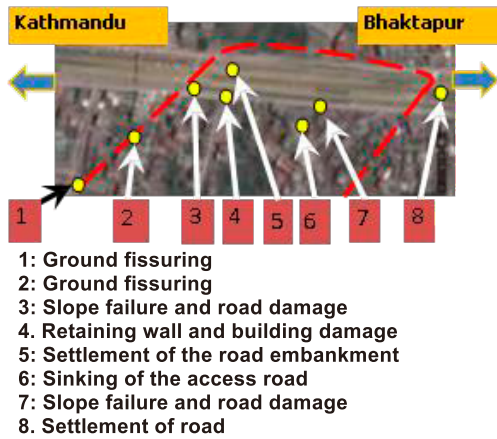


Fig. 5. Locations of the damaged area in the main road and the access road (Source map URL: <http://www.maps.google.com>).



Fig. 6. Slope failure in the Kathmandu side.



Fig. 7. Slope failure and subsidence (Bhaktapur side) (a) main road and (b) access road.



Fig. 8. Slope failure and subsidence (Bhaktapur side) (a) subsidence of the access road and (b) tilted apartment building.

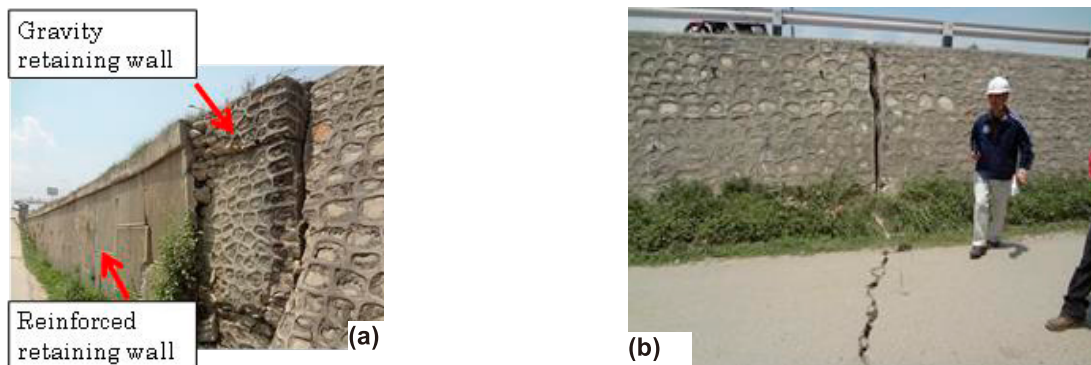


Fig. 9. Retaining wall damage and ground fissuring (a) damage to retaining walls and (b) ground cracks.



Fig. 10. Settlement and tilting of buildings resulting from ground fissuring.

Fig. 11. Ground fissuring in the surveyed area (a) observed ground fissuring and (b) fissure orientation in the area.

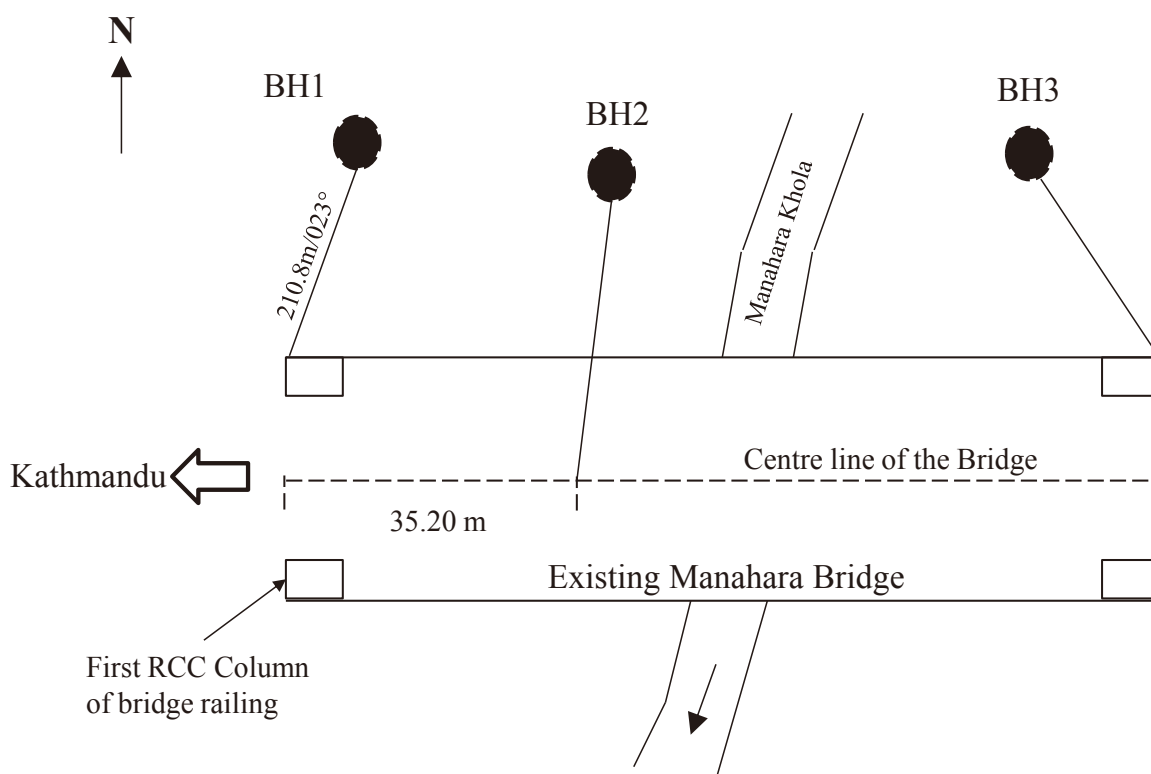


Fig. 12. Borehole locations around Manahara bridge (JICA, 2007).

Ground fissuring was also observed in many locations around the residential area surrounding the access roads. **Fig. 11(a)** shows one of those having a maximum width of 20 cm. Ground fissuring in 30° azimuth towards the east was observed. Such ground cracking was observed not only in the road embankment but also continued within a wide area both towards the left and right side of the road embankment. The angle of ground fissuring is almost the same in both sides of road embankment and of was 400 m in length towards the south west (**Fig. 11b**).

3.2 Damage to the road and surrounding infrastructures

No detailed geotechnical information about the soil characteristics in the Lokanthali area is available. The closest information available is from the three borehole locations near 84m long Manahara bridge (**Fig. 12**) which is located less than 1 km from Lokanthali (JICA, 2007). **Figure 13** shows the geological profile of the borehole no. 3 (location close to Lokanthali).

From **Fig. 13** it is clear that the area is mostly dominated by very thick layer of compressive clay. Settlement of this clay deposits and possible amplification of motion may have resulted in such localized damage in this part of the Kathmandu-Bhaktapur road. However, detailed borehole information adjacent to the site and other geotechnical survey results are necessary to arrive at a definite conclusion.

4. Damage to historical sites

Nepal is nonetheless home to eight UNESCO World Heritage cultural sites. That includes three royal cities and several Hindu and Buddhist sites within the Kathmandu Valley, as well as Lumbini, the legendary birthplace of the Buddha, all of which are in the area affected by the earthquake. Many of those centuries-old buildings and monuments were destroyed in the Kathmandu Valley, including some at the Kathmandu Durbar Square, the Patan Durbar Square, the Bhaktapur Durbar Square, the Changu Narayan temple and the Swayambhunath temple. In the following subsections few examples of damage inflicted on those historical buildings and monuments, word heritage sites and historic town are discussed.

4.1 Damage at Kathmandu durbar square

Several pagodas on Kathmandu Durbar Square, a UNESCO World Heritage Site, collapsed. The Dharahara tower in that square, built in 1832, completely collapsed leading to death of at least 180 people including

honeymoon couples. **Fig. 14** shows the states of the tower before and after the earthquake.

4.2 Damage at Patan durbar square

Patan, famous as the oldest city in Kathmandu valley, is also known as the city of fine arts. Another name of Patan, is Lalitpur. The exquisite artworks and architectural buildings, scattered in and around Patan Durbar square, are from 16th century and onwards. In 1979 they were listed in the world heritage monument. It is probably one of the oldest Buddhist Cities in the world. The city is situated on a plateau across Bagmati River. In Patan, the Char Narayan Mandir, the statue of Yog Narendra Malla, a pati inside Patan Durbar Square, the Taleju Temple, the Hari Shankar, Uma Maheshwar Temple and the Machhindranath Temple in Bungamati were destroyed during the earthquake.

Figure 15 is a 2010 photo of the intact temples. Several of the tiered temples appear to have collapsed. **Fig. 16** shows the Harishankar temple, built in 1706 and one of the most outstanding temples in Patan before and after the earthquake.

4.3 Damage at Bhaktapur durbar square

In Bhaktapur durbar square, several monuments, including the Fasi Deva temple, the Chardham temple and the 17th century Vatsala Durga Temple, were fully or partially destroyed. **Figure 17** shows the famous Hindu temple (Vatsala Durga temple) before the earthquake. Built in 1672, this beautiful stone building was a favorite for many people to sit out on and watch the sunset in Bhaktapur durbar square. It is no more than rubble now (**Fig. 18**). Few other temples (**Fig. 19**) in the square were also seriously damaged including a school building which completely collapsed (**Fig. 20**).

4.4 Damage to Changu Narayan temple

One of the oldest Hindu temples in Nepal, Changu Narayan is believed to have been built in the 5th century A.D. Located on a hilltop east of Kathmandu, the two-tiered pagoda (**Fig. 21**) is considered one of Nepal's most unique architectural monuments. Constructed on a single slab of stone, the Changu Narayan temple had withstood the large earthquake of 1934 Bihar-Nepal Earthquake. This time earthquake inflicted some damage to this main temple as seen from the scaffolding of the temple after the earthquake (**Fig. 22**). Two of the four temples on the premises of Changu Narayan square have been reduced to rubble by the earthquake (**Fig. 23** shows one of them).

Location: Manhara Khola						BOREHOLE No. - BH3	
FIELD AND LABOTARY DATA AND TEST REPORTED ELSEWHERE	WATER CONTENT (%)	DRY DENSITY (G/cm3)	SPT/CPT 'N'	DEPTH (m)	RUN (m)	GRAPHIC SYS	COORDINATES: N E M GROUND ELEVATION: DESCRIPTION OF STRATA
				0			Moist and damp area of compressive soil.
				1			Very compressive soil.
	45.12	1.26	9	2			Boulders and gravels
	43.44	C=10.43kN/m2		3			Lead gray, stiff to very stiff compressive silty clay
			27	4			
	40.89		30	5			
			14	6			
		1.03	15	7			Grey to dark gray, stiff compressive silty clay
	58.33	C=15.64kN/m2	13	8			
				9			
	60.58		13	10			
		0.79	13	11			Grey to dark gray, very stiff compressive clay with very les amount of silt
	86.37	C=41.40kN/m2	27	12			
			27	13			
	86.37		30	14			
				15			
		0.79		16			
	84.75	C=60.77kN/m2	30	17			
			29	18			
			28	19			
			30	20			
				21			
Ground Observation: 1.00m							
Project: Basic design study on the project for improvement of Kathmandu-Bhaktapur Road in Nepal					SUMMARY BORING LOG		
CLINT/OWNER: Nippon Koei-(JICA)					Starting date: 13/12/2006		Completed date: 16/12/2006
Consulting Engineers: ITECO Nepal in association with ICGS					Job No. 3351		Sheet No. 1

Fig. 13. Soil profile at borehole no. 3 (JICA, 2007).



Fig. 14. State of damage of Dharahara tower.



Fig. 15. Patan square before the earthquake (Photo courtesy: Narendra Shrestha).



Fig. 16. Harishankar temple before and after the earthquake.



Fig. 17. Vatsala Durga temple before the earthquake.



Fig. 18. Vatsala Durga temple after the earthquake.



Fig. 19. States of other temples and buildings in Bhaktapur square.



Fig. 20. Collapsed school building (only the gate remains) in Bhaktapur square.



Fig. 21. Two-tiered pagoda in Changu Narayan.



Fig. 22. Two-tiered pagoda after the earthquake protected by scaffolding.



Fig. 23. One of the collapsed temples in Changu Narayan.



Fig. 23. Sayambhunath temple complex.



Fig. 24. Damages in Sayambhunath temple complexes.

4.5 Damage to Swayambhunath temple

Comprising temples, shrines and the iconic stupa which bears the painted on eyes of the Buddha the 150 year old Swayambhunath (also known a monkey temple) is not only a revered location for locals, but also one of the most-visited tourist destinations in the capital (**Fig. 24**). Swayambhunath temple complex in the Kathmandu Valley suffered heavy damage due to the earthquake. Few structures within the temple complex suffered damage (**Fig. 25**).

4.6 Damage to historic town of Sankhu

Sankhu is the ancient town, with predominant Newari culture, located in the north-eastern corner of Kathmandu Valley in about 17 km from the capital city Kathmandu. Sankhu is probably the worst affected historical town, where 80 to 90 % of the buildings were completely collapsed.

Figure 26 shows the view of the buildings in the town before the earthquake. **Figure 27** shows the state of the same buildings after the earthquake. Total collapse of many structures in the city were observed here and there (**Fig. 28**).

5. Damage to modern buildings

Not only the historical monuments and old brick masonry buildings, but many recently built and comparatively well-engineered buildings including multistory business complexes and apartment buildings were also heavily damage. In recent years, especially during the last one decade, Kathmandu valley has had a sharp rise in the number of multistory business complexes and apartment buildings, mainly constructed of reinforced concrete framed structure with brick masonry infill. Most modern residential and commercial buildings also follow the similar construction practice, but a large number of these buildings have been constructed without adequately incorporating the seismic design criteria. Even within the Kathmandu valley, which is the most densely populated urban settlement of the nation, most peripheral areas enjoyed waiver of the administrative process of construction permit up until a couple of years ago. Moreover, in many occasions, manipulation of the design data and use of substandard material quality have also added to poor seismic capacity of the buildings.

The trend of damage to reinforced concrete buildings during this earthquake can be categorized into two main patterns: 1) column breakage and severe structural tilting



Fig. 26. View of Sankhu town before the earthquake.



Fig. 27. View of the spot in Fig. 15 after the earthquake.



Fig. 28. Few selected collapsed structures in the town.



Fig. 29. A typical case of damage to comparatively short buildings.



Fig. 30. A typical case of damage to comparatively short buildings.

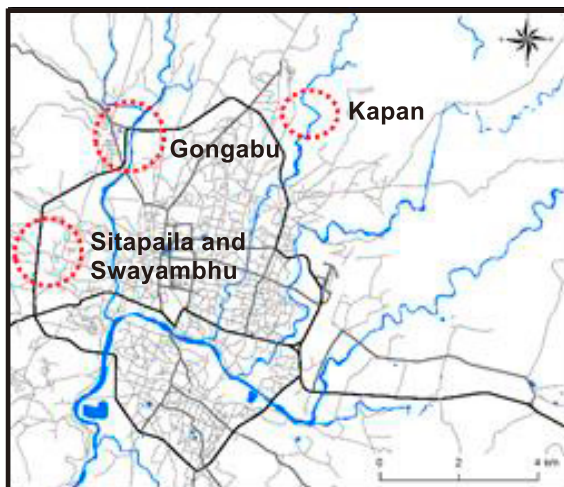


Fig. 31. Core Kathmandu and Patan area.

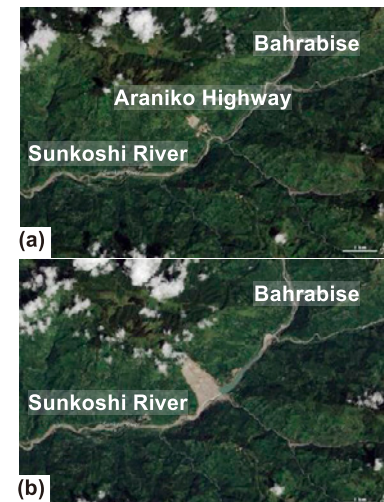


Fig. 32. Landslide in Jure (a) before the landslide and (b) after the landslide (Courtesy: NASA).

or complete collapse in comparatively short buildings (i.e. 3-6 story), as in Fig. 29 and 2) massive shaking and heavy damage to non-structural elements, such as brick masonry partition walls, in comparatively tall buildings (i.e., >10 story), as in Fig. 30. Leaving aside a few cases of complete collapse in other locations, damage to short buildings was concentrated in some pocket areas, such as Gongbu, Swayambhu, Sitapaila, and Kapan (Fig. 31). However, most such buildings in central core were not affected much except for a few cracks in the walls. On

the other hand, out of more than 50 tall buildings in Kathmandu and Patan, more than 40 were found to have sustained medium to heavy damage, mainly in non-structural parts (Fig. 30).

Kathmandu valley is filled with soft sediment deposit composed primarily of lacustrine material that goes as deep as 500 meters in the center. Borehole logs of different times are also evident that a larger part of the sediment deposit is composed of organic clayey material. Despite the fact that the bearing capacity of this clayey

sediment is extremely weak, most buildings in Kathmandu valley have been constructed on isolated or raft footing foundation. Some of the tall buildings were found to have been tilted, which is due to poor bearing capacity of the foundation soil.

6. Compound disaster in Sunkoshi area

6.1 Jure landslide

A massive landslide occurred at around 02.30am, local time on August 2, 2014 at Jure village in Sindhupalchowk district of Nepal. The landslide killed 156 people, injuring 27 and displacing 436 people.

The massive landslide blocked Sunkoshi River creating a high dam across the river (**Fig. 32**). A river gauging station of the Department of Hydrology and Meteorology (DHM) at Pachuwarghat downstream of the landslide dam showed a rapid decline in water flow three hours after the landslide, after which the flow of water completely stopped for approximately 12 hours. An inflow of about 160 m³/sec of water quickly created a large lake behind the dam. Within 13 hours the newly formed lake, which rapidly grew to a volume of an estimated 7 million cubic meters, extended about 3 km upstream, completely submerging the 2.6 MW Sanima hydropower station (**Fig. 33**).

The landslide-dammed lake also has created havoc amongst the local residents and people living in the downstream and upstream riverside areas. The landslide completely obstructed the Araniko Highway, and it was not possible to pass through the landslide further to the north, disrupting the transportation network to China, and braking the national daily revenue of about 30 million Nepali Rupees.

6.2 Damage to Sanima Sunkoshi Power Plant due to landslide

The landslide at Jure has swept away two gates of the Sunkoshi power house headworks. The power house was also submerged after damage to the project's penstock. The powerhouse and the camp house lied at the sediment deposition zone. The lake inundated most of the equipment/materials in powerhouse and camp house. **Figures 34 (a)-(b)** show the state of the damage before and after the landslide.

Private development firm (Sanima Hydropower Plant) undertook the repair and reconstruction works of the dam and it was ready for commissioning on May 1, 2015.

6.3 The compound disaster

However, there is big blow to the works by the earthquake of April 25, 2015. The power house was damaged at various places by the earthquake as seen in **Figs. 35 (a-d)**. The earthquake also induced shallow landslides on the upstream and right bank of the power station as shown in **Figs. 36 (a and b)**.

The landslide related loss to the power plant amounts to 148 million Nepali Rupees. The earthquake damage was estimated to be 34 million Nepali Rupees. Total damages from this compound disaster stand at 203 million Rupees.

7. Possible reasons of the damage and lessons learned

The acceleration, velocity, displacement profiles (**Fig. 37**) and spectral distribution (**Fig. 38**) of the earthquake reveal that the maximum acceleration (about 182 Gal) is not that high. However, the velocity, which is a barometer for generated earthquake energy, is rather high. Also, the spectral distribution of acceleration reveals that it was a long-period motion.

Most of the damage can be contributed to the non-engineered structures (combination of sunburnt brick and clay mortar), which have negligible resistance to earthquake type loading. Also, damage were mostly localized, which indicate the possibilities of resonance due to ground motion amplification in Kathmandu valley, which basically compose of soft alluvial deposits in old rivers and lakes (**Fig. 39**). The Kathmandu valley comprises of thick semi-consolidated fluvio-lacustrine Quaternary sediments on the top of basement rocks. Piya (2004) reports that the maximum thickness of the valley sediments reaches up to 550 m at the central part of the valley. The shear wave velocity of the soft sedimentary deposits ranges between 167 m/s and 297 m/s, and ground amplification may be ranging between 1.9 and 7.9 according to Chamlagain and Gautam (2015). Due to complicated geology of the Kathmandu valley two levels of resonance are expected (Paudyal et al., 2012).

The attenuation of acceleration distribution is shown in **Fig. 40**. It was observed that the damage in most of Kathmandu City, closest to the epicenter, was minor, however, the eastern part of Kathmandu was extensively damaged even though it was further from the epicenter. The extensively damaged areas were located in the north-east of the Kathmandu valley. **Figure 40** is a map projection of the final-slip distribution, using fully Bayesian multiple-time-window source inversion (Kubo et



Fig. 33. Submerged power station (Courtesy: Sanima Hydropower Ltd., Kathmandu).

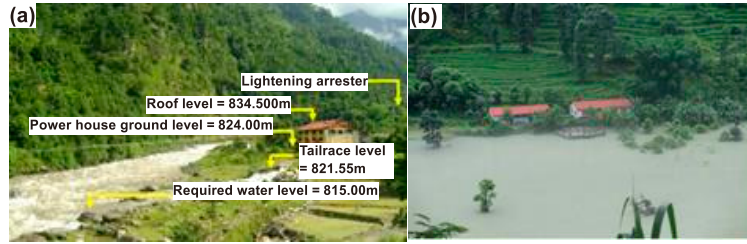


Fig. 34. State of the power station (a) before the landslide and (b) after the landslide (Courtesy: Sanima Hydropower Ltd., Kathmandu).



Fig. 35. Earthquake induced damage to the power station (a) wall collapse on riverside (b) rupture of reinforcement bar (c) operator's camp at headworks and (d) machine floor.



Fig. 36. Earthquake induced landslide (a) landslide in the upstream of intake and (b) landslide in the right bank of headworks.

al., 2016). It reveals that the rupture process extended to the east side of Kathmandu City.

8. Conclusions and recommendations

The following conclusions and recommendations could be made based on this preliminary survey of the earthquake damage of the structures.

- The damage to newly built building structures was concentrated at particular pocket areas and more specifically in newly developed sub-urban areas of the Kathmandu city core.
 - Most old brick masonry buildings were heavily damaged throughout the valley, and the destruction was particularly found to be concentrated in Bhaktapur city core and Sankhu area of Kathmandu.
 - One typical characteristic of the damage pattern found this time was that, comparatively little damage
- to hospital buildings and life-line infrastructures including power line, water pipes, communication network, and roads. The only international airport in Nepal was reported to be totally undamaged.
 - Immediate geotechnical and geological investigations of the soils in the vicinity of historical monuments are required.
 - Reconstruction and retrofitting measures to be adopted considering acceleration amplification in future earthquakes.
 - It is very important to take into the account the effect of soil stratum (surface and lower layers) and the velocity distribution profiles based on geotechnical data base.
 - New approaches in the geotechnical design and retrofitting of foundations, which are cost-effective and locally available, require immediate attention.
 - Use of information technology and local participation towards disaster mitigation also need attention.

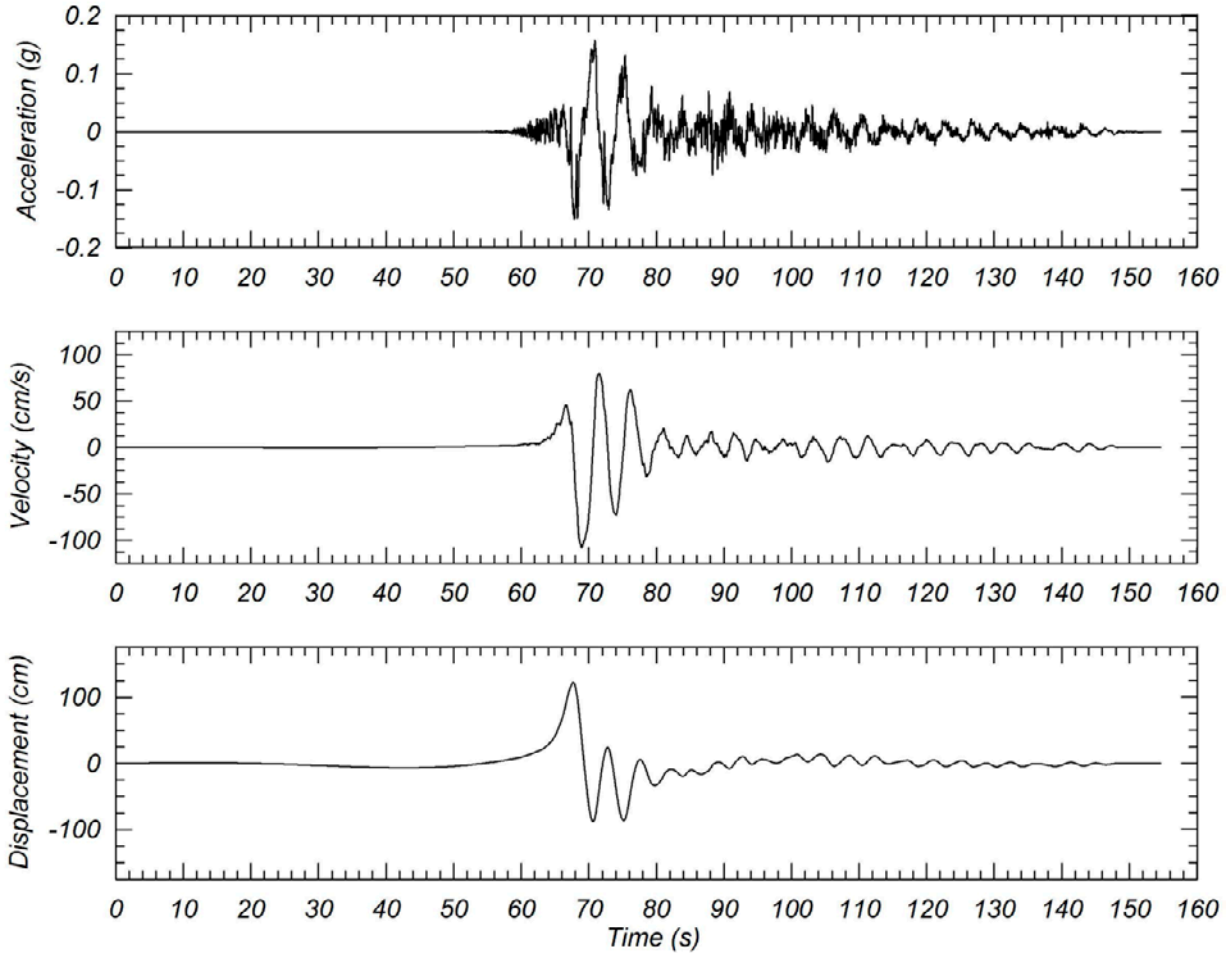


Fig. 37. Acceleration, velocity and displacement profiles of the earthquake (Source: USGS).

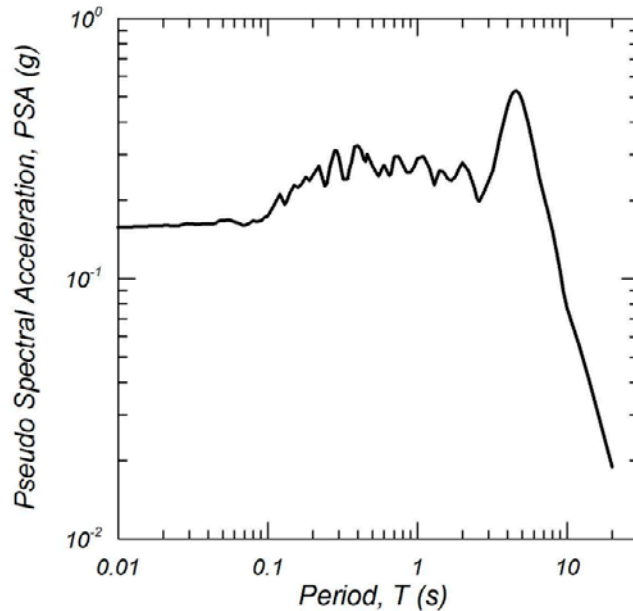


Fig. 38. Spectral distribution (Source: USGS).

i. Rebuilding the historical sites this time around, especially the older ones, will be no easy task. In the

retrofitting of the historical monuments in the Kathmandu valley, it is very important to collect infor-

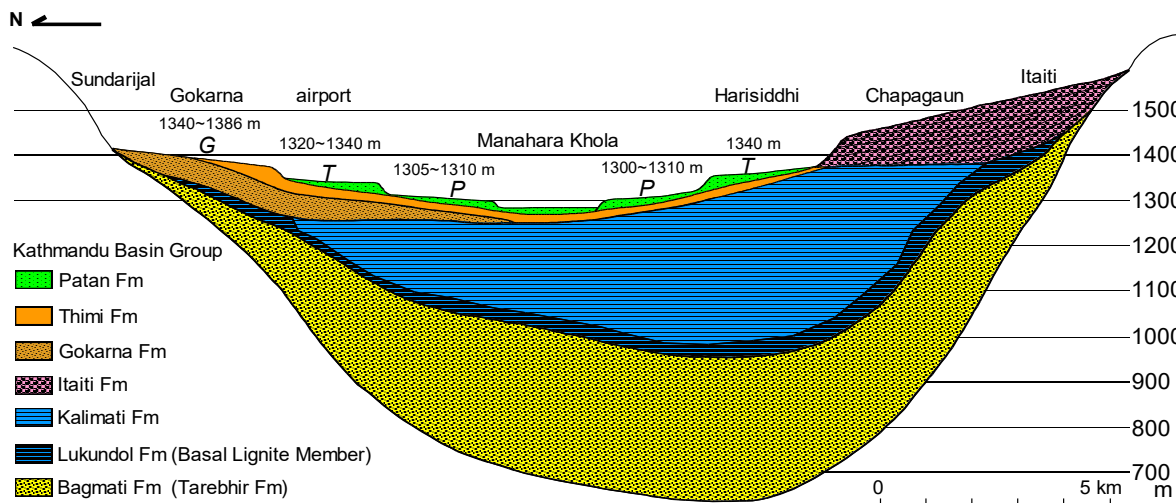


Fig. 39. Schematic geological cross section of Kathmandu valley along N-S (Sakai, 2001).

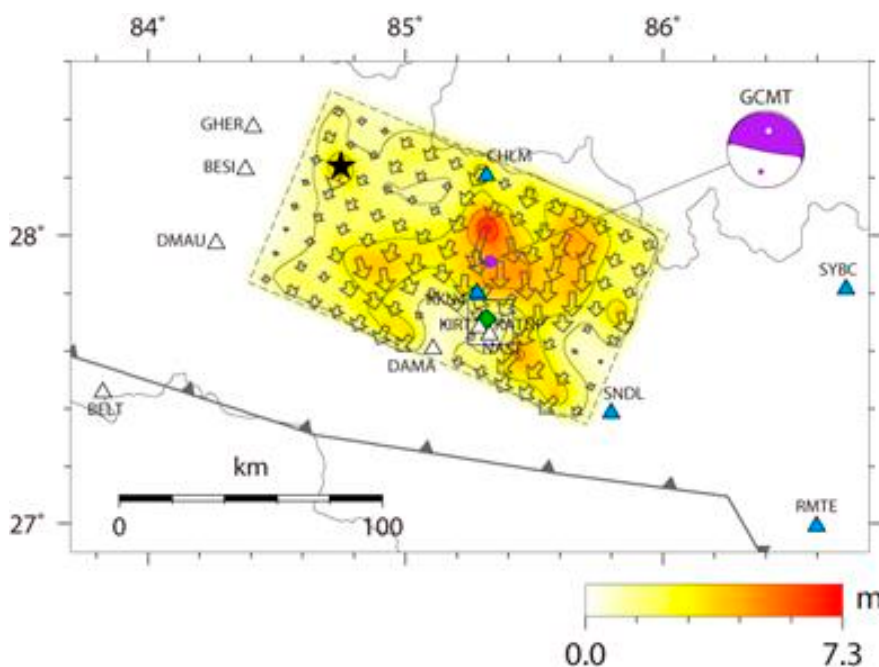


Fig. 40. Map projection of the final-slip distribution (Kubo et al., 2016).

mation regarding the foundations of those structures. That is definitely going to be a challenging task for geotechnical engineers and researchers in the years to come.

Acknowledgements

The financial support provided by Kyushu University under the special grant of the president, Kyushu University towards the survey is greatly appreciated. The authors also gratefully acknowledge Assoc. Prof. Ranjan

Kumar Dahal, Tribhuvan University for his tremendous help and cooperation during their survey.

References

Bilham, R., Bodin, P. and Jackson, M., 1995. Entertaining a great earthquake in western Nepal: Historic inactivity and geodetic tests for the present state of strain. *Journal of Nepal Geological Society*, **11** (1): 73-78.

- Bilham, R., Larson, K., Freymuller, R. and Members, P.I., 1997. GPS measurements of present-day convergence across the Nepal Himalaya. *Nature*, **386**: 61-64.
- Chamlagain, D. and Gautam, D., 2015. Seismic hazard in the Himalayan intermontane basins: An example from Kathmandu Valley Nepal. *Mountain Hazards and Disaster Risk Reduction*: 73-103.
- JICA (Japan International cooperation Agency), 2002. The study of earthquake disaster mitigation in Kathmandu valley, Kingdom of Nepal. Final Report, **I, II, III, IV**.
- JICA (Japan International cooperation Agency), 2007. Planning for improvement of Kathmandu-Bhaktapur road in the Kingdom of Nepal, Report on the preliminary design and investigation.
- Kubo, H., Dhakal, Y.P., Suzuki, W., Kunugi, T., Aoi, S. and Fujiwara, H., 2016. Estimation of the source process of the 2015 Gorkha, Nepal, earthquake and simulation of long-period ground motions in the Kathmandu basin using a one-dimensional basin structure model. <http://dx.doi.org/10.1186/s40623-016-0393-5>.
- Mukhopadhyay, B., 2011. Clusters of moderate size earthquakes along main central thrust (MCT) in Himalaya. *Intl. J. Geosciences*, 2011, doi:10.4236/ijg.2011.23034 Published online August 2011, **2**: 318-325.
- NASA. <http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=84406>, retrieved on September 15, 2016.
- NSET and GHI, 1999. Earthquake scenario, product of the Kathmandu valley earthquake risk. management project, National Society for Earthquake Technology-Nepal (NSET-Nepal) and GeoHazards International (GHI).
- Paudyal, Y.R., Yatabe, R., Bhandary, N.P. and Dahal, R.K., 2012. A study of local amplification effect of soil layers on ground motion in the Kathmandu valley using micro tremor analysis. *Earthquake Engineering and Engineering Vibration*, **11** (2): 257-268.
- Piya, B.K., 2004. Generation of a geological database for the liquefaction hazard assessment in Kathmandu valley. MSc Thesis, International Institute for Geo-Information Science and Earth Observation, Enschede, the Netherlands.
- Sakai, H., 2001. Stratigraphic division sedimentary facies of the Kathmandu basin group, Central Nepal. *J. of Nepal Geol. Soc.*, Special Issue, **25**: 19-22.
- Sakai, H., Sakai, H., Yahagi, W., Fuji, R., Hayashi, T. and Upreti, B.N., 2006. Pleistocene rapid uplift of the Himalayan frontal ranges recorded in the Kathmandu and Siwalik basins. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **241** (1): 16-27.