Engineering Geological Issues after Gorkha Earthquake 2015 in Nepal - a preliminary understanding

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Abstract

Nepal is one of the earthquake-prone countries in the Himalayan region and earthquakes in Nepal have been reported since 1255. Recent Gorkha Earthquake measuring M_w7.8 occurred at 11:56 AM Nepal Standard Time on 25 April 2015 with an epicenter 77 km northwest of Kathmandu at Barpak village of Gorkha district and killed more than 8900 people. This earthquake was the one of the most powerful earthquakes to strike central Nepal since the 1934 Nepal-Bihar earthquake. Earthquake-induced landslides, land subsidence, and liquefaction are major engineering geological issues after the 2015 Gorkha Earthquake in central Nepal. In the case of the Gorkha Earthquake, topographic effect is quite well observed in many towns and villages on ridge in mountainous regions. Many houses on the ridge were damaged and many tension cracks were observed on ridges. Rock fall, shallow landslides and dry debris fall, deep seated landslides, debris flow and avalanche, valley fill collapse and cut-and-fill failure are major earthquake-induced landslides in the affected area of the Gorkha earthquake. More than 40% of house damage in Kathmandu valley was found to be caused by differential settlement of the land in Kathmandu Valley lacustrine sediments. Along with land subsidence, a few sand boils were observed in Kathmandu valley due to liquefaction of the lower strata.

Keywords: Gorkha Earthquake, Nepal, Himalaya, Earthquake-induced landslide, Liquefaction, Land subsidence

1. Introduction

Being located in central part of the Himalayan ranges, Nepal is regarded as one of the earthquake-prone countries in the region. Earthquake is a major concern of Nepal because of rapid population growth, poor land use planning, precarious settlement patterns, and poorly implemented building code. Earthquakes in Nepal have been reported since 1255 while major earthquakes were recorded in 1408, 1681, 1810, 1833, and 1866, 1934, 1980, 1988, and 2011. Recent Gorkha Earthquake measuring M_w7.8, killed more than 8900 people and injured thousands of people. The Gorkha Earthquake occurred at 11:56 AM Nepal Standard Time on 25 April 2015 with an epicenter 77 km northwest of Kathmandu at Barpak village. This earthquake was the one of the most powerful earthquakes to strike Nepal since the 1934 Nepal-Bihar earthquake. It is estimated that more than eighty five million people have been affected by the Gorkha Earthquake in Nepal. This is equal to the quarter of the Nepal's population.

Earthquake-induced landslides, land subsidence, and liquefaction are major engineering geological issues after the 2015 Gorkha Earthquake. Earthquake-induced slope failures are one of the most damaging natural disasters. Commonly, damage from earthquake-induced slope failures is worse than damage related to the shaking and rupture of the earthquake itself. When earthquake-induced landslides in Nepal is concerned, there were many incidents. But, the record on the earthquake-induced slope failures is not well documented. Few documentations has been done during 2011 Sikkim-Nepal border earthquake in Taplejung district (Dahal et al., 2013). In the Gorkha Earthquake also, many landslides are occurred in the major hit area and basically the distribution of landslides is concentrated in Barpak to Dolakha, mainly northern part of Kathmandu valley. This paper will share preliminary understanding of landslides in earthquake affected districts. It also deal with a few land subsidence problems and damages in infrastructures in and around Kathmandu valley.

2. Geological and tectonic settings of the Nepal Himalaya

The Himalaya belongs to very high seismic region and has a history of devastating earthquakes. The major source of earthquakes in Nepal and the Himalayan Region is the subduction of the Indian plate underneath the Eurasian plate, which causes contraction and stress concentration. Seismicity of the Himalayan region has been studied in terms of its relationship with known tectonic activities (Rai et al., 2004). During the past 100 years, three great earthquakes occurred along the Himalayan front (Ambraseys and Bilham, 2000). From west to east, they includes the 1905 Kangra Earthquake (Ms ~7.8), the 1934 Bihar-Nepal Earthquake (Mw = 8.1), and the 1950 Assam Earthquake (Mw ~8.6). Although none of these earthquakes is reported to have produced primary surface rupture (Seeber and Armbruster, 1981), on the basis of isoseismal map and location of damage, it is estimated that these earthquakes are the result of slip on the Main Frontal Thrust (MFT). Same case appeared in the cases of the Gorkha Earthquake, where seismologists still could not trace out primary surface rupture. Therefore, this earthquake also regarded as the case of the strain release on blind thrust and it can be expressed as anticline growth rather than primary surface rupture or co-seismic surface rupture in and around Kathmandu valley (Fig. 3). However, Avouac et al. (2001) have mentioned that previous earthquake events have produced a rupture of 250-300 km in the Himalayan arc together with a co-seismic slip of estimated average length of 5 km.

The southern part of the Himalaya, i.e. Ganges Delta of northern India has extremely high population density is in an area very close to historic great earthquakes, demonstrated high strain accumulation (Fig. 1).

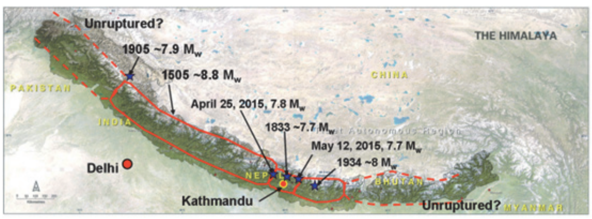

Fig. 1 Major earthquakes in the Himalayan region, modified after Zurick et al.(2005) and USGS (2015)

Geologically and tectonically, Nepal is divided into five major tectonic zones, namely, Terai Zone, Siwalik Zone, Lesser Himalayan Zone, Higher Himalayan Zone and Tibetan-Tethys Himalayan Zone (Ganser, 1964). These tectonic zones are separated by major thrusts and faults of the Himalaya and those faults and thrusts are named from north to south (Fig. 2) as South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT). Likewise, geomorphologically, Nepal is divided into eight units running east-west, namely, Terai, Churia Range, Dun Valley, Mahabharat Range, Midland, Fore Himalaya, Higher Himalaya, Inner and Trans Himalaya (Dahal and Hasegawa, 2008).

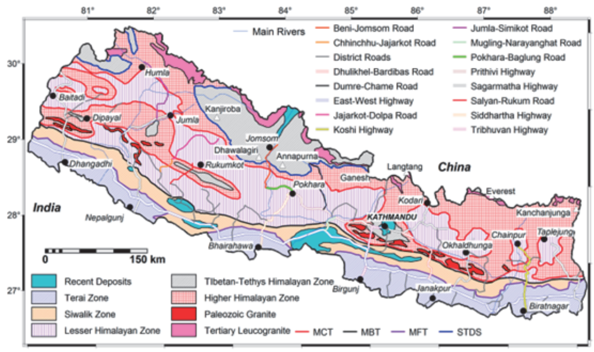

Fig. 2 Geological map of Nepal with major road networks (modified after Dahal and Hasegawa (2008)

Generalized cross section is shown in Fig. 3 and it illustrates 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.

3. Earthquake Characteristics and Fault Displacement

As mentioned in earlier section, 7.8 M_w was main shock on 04-25 at 77 km NW of Kathmandu. More than ~100 subsequent aftershocks were occurred eastward of main shock. M 7.3 M_w aftershock hit on 05-12 at 80 km NE of Kathmandu. Most earthquakes are shallow angle thrust faulting on decollement of Main Frontal Thrust (see Fig. 3). Main shock slip was directed towards east from hypocenter with peak slip about 4 m (USGS, 2015). The block dimensions is approximately 120 x 80 km. Shaking estimates in epicenter region are poorly constrained due to fewer intensity observations and absence of strong ground motion data. Likewise, predominantly strong to very strong shaking were focused around aftershock hypocenter and severe shaking was elongated eastward from Barpak (epicenter of April 25, 2015) to Dolakha (May 12, 2015) as shown in Fig. 3.

The aftershock distribution outlines the rupture zone of the main shock. The rupture during the main shock initiated beneath the epicenter and propagated toward the southeast. Fig. 4 shows fault displacement during the Gorkha Earthquake. The star is the epicenter while the thick arrow shows the direction of rupture propagation towards the south east direction.

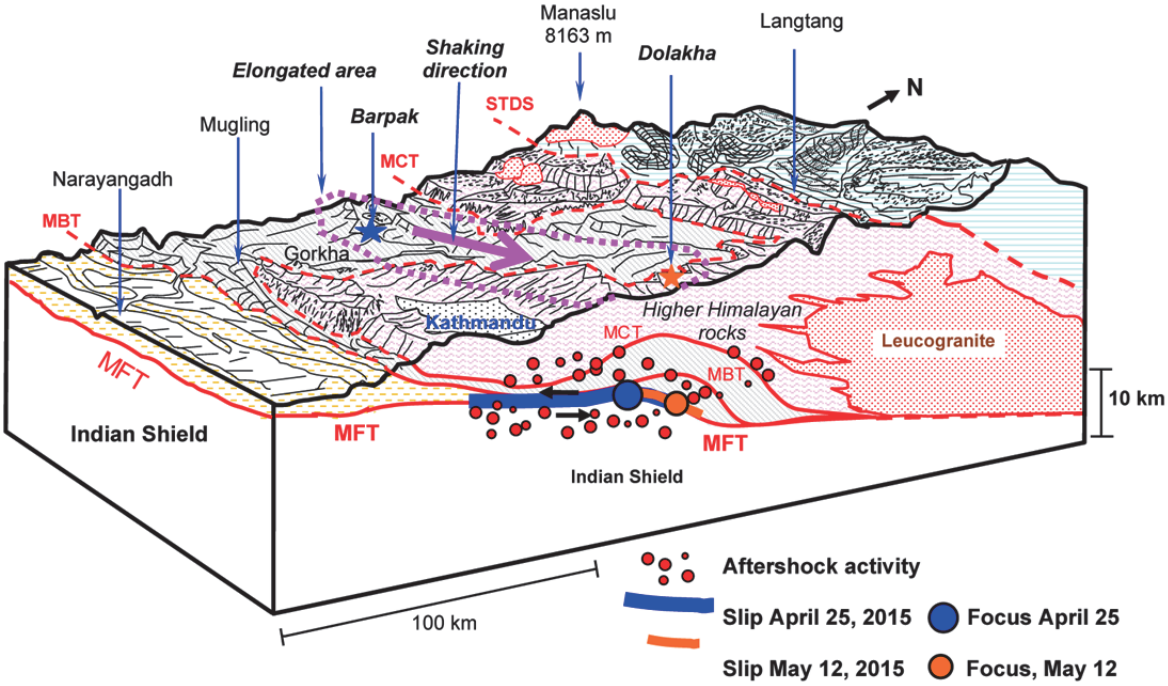

Fig. 3 Block diagram of area affected by 2015 Gorkha Earthquake, Generalized cross section showing the approximate locations of slip during the 25 April and 12 May 2015 ruptures on the Main Frontal Thrust (MFT). Locations of both Barpak and Dolakha epicenters as well as aftershocks are schematic only and all are projected on vertical plane of sight. The elongated area faced strong-severe damages/shaking and it is extended towards east up to Dolakha. The block model is modified after (Hasegawa et al. 2009).

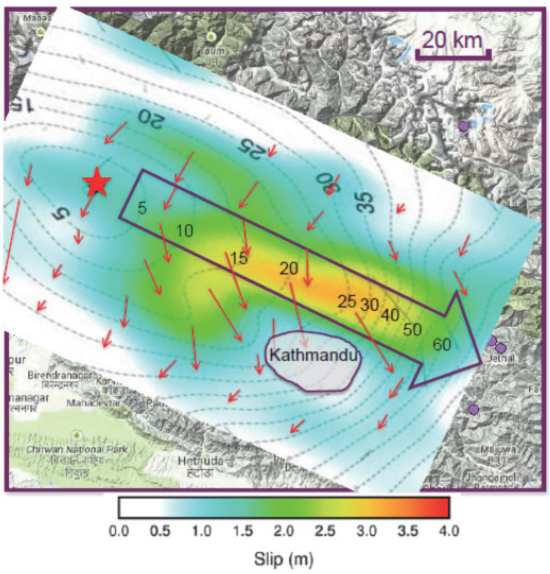

Fig. 4 Fault displacement during Gorkha Earthquake (IRIS, 2015)

Contours show the rupture front in 5 second increments after rupture initiation. Small red arrows show the direction and amount of motion of the rocks above the fault with respect to the rocks below the fault. The amount of slip is shown by color of shading. Maximum fault displacement of about 3 meters occurred in the rupture zone in 20 km north of Kathmandu (IRIS, 2015).

4. Ground response in Kathmandu valley

Kathmandu valley is an intermontane basin and it has soft soil layers of lacustrine origin. Borehole log analysis in different region of the valley shows that the lacustrine soil is very complex in nature, and properties and soil thickness is vary from place to place. From borehole data, the maximum depth of the deposit goes as high as 500 m in central part of the valley. These large variations in sediment thickness and in soil properties are responsible for change in characteristics of the seismic waves and amplification process of the strong ground motion. Not only in the Gorkha earthquake but also in the Bihar-Nepal Great Earthquake (Mw = 8.1) of 1934 ground shaking of the Kathmandu valley from earthquakes suggest that spectral amplification is common in Kathmandu and lacustrine sediments in the valley is playing the major role in the intensification of ground motion. From the rapid damage assessment in the valley after the Gorkha Earthquake, it is found that the most of damages were concentrated in northern part of the valley. Center part of valley faced damaged on high rise structures. Southern part of the valley also faced damages but basically damages were concentrated on adobe old buildings and temples only.

This earthquake was destructive because it is shallow earthquake (15 km), and Kathmandu valley it self lies in a basin filled with about 300 m of soft sediment. Sedimentary basins can have a large effect on ground motion above them. Earthquake waves travel at high velocity through the stiff, metamorphic rock of the valley but slow dramatically when entering the basin possessing long period-low frequency nature. This increases the amplitude of the earthquake waves within the basin fill. In addition, the sharp density contrast of the soft basin rocks with surrounding material can cause waves to reflect, trapping energy in the basin for a period of time. This extends the duration of shaking (IRIS, 2015).

Being a bowl shaped valley with thick (more than 300 m in many places) lacustrine sediment, Kathmandu valley is in great risk of earthquake. The soil type, ground response, building types and soil depth are not well known to the concerned governmental agencies and even to the engineers. Still researches are very few and evidences and geotechnical clues of the hidden materials beneath the valley are still not well known. The variation of predominant frequency (Fig. 5) determined by Poudyal et al. (2012) for Kathmandu valley fits approximately with the damage distribution in the valley after the Gorkha Earthquake. After the Gorkha Earthquake, the Government of Nepal is realizing a urgent need of detail investigation and research for earthquake risk in the Kathmandu valley.

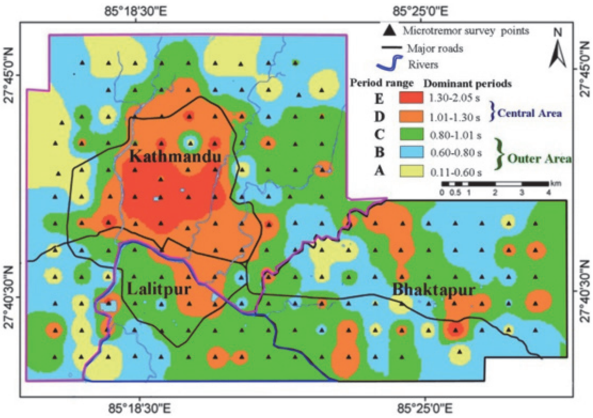

Fig. 5 Dominant natural period of ground of Kathmandu from microtremor analysis (after Poudyal et al. 2012)

5. Topographic effect and earthquake damages

The various investigations showed that topographic features are basically responsible for dissipation of seismic energy (e.g. Gilbert and Knopoff, 1960) and extremely high accelerations are usually observed at sites located on topographic ridges (Ambraseys and Srbulov, 1995; Miles and Keefer, 2000; Lin et al., 2003; Uchida et al., 2004). Observations of the damage patterns of earthquakes, such as the 1987 Whittier Narrows, California earthquake, the 1989 Loma Prieta (California) earthquake, the 1994 Northridge, California earthquake, the 1999 Chi-Chi earthquake of Taiwan, the 2004 Chuetsu earthquake of Niigata Prefecture, Japan, the 2005 Kashmir earthquake of Pakistan and the 2011 Sikkim-Nepal Earthquake of Nepal also indicate the occurrence of intense shaking in elevated ridges of rugged topography.

Geli et al. (1988) have reported that buildings on crests suffer more damage than those located at the base and they conclude that there is always significant amplification of frequencies corresponding to wavelengths about equal to mountain width at hilltops with respect to the base. In the case of the Gorkha Earthquake, it is quite well observed in Chautara town in Sidhupalchowk District. Many houses on the ridges were damaged and many cracks were observed on ridge (Photo 1). Similarly, an amplification-deamplification pattern on slopes leads to a strong energy differential on the upper part of the slope. For the preliminary site visit of the Gorkha Earthquake, it is understood that landslide frequency is much higher on or near the crests of hills and mountains.

Photo. 1 Old Chautara town on ridge and damaged houses

6. Engineering Geological issues

Three major engineering geological issues observed after the Gorkha Earthquakes are earthquake-induced landslides, land subsidence and liquefaction. Brief information of each issue are described below.

6.1 Earthquake-Induced landslide

As in the other part of the world, earthquake induced landslides after Gorkha Earthquake is also can be classified in terms of six categories as follow:

1. Rock fall
2. Shallow landslides and dry debris fall
3. Deep seated landslides
4. Debris flow and mud flow
5. Valley fill collapse
6. Cut-and-fill failure

Rock fall were very common along the road side slope after the Gorkha Earthquake. Especially, Liping

Bazaar area, near to the Nepal-China border faced tremendous damages due to rock fall and boulder falls (Photo 2). Shallow landslides were common problems in the mountains at northern part of Kathmandu valley. The damages were mainly concentrated on Dhading, Nuwakot, Rasuwa and Sindhupalchowk, Dolakha districts.

Deep-seated landslide is was not much after the Gorkha Earthquake, but few failures are seen in old landslide mass (Fig. 5) in the Rasuwa district, north of Kathmandu.

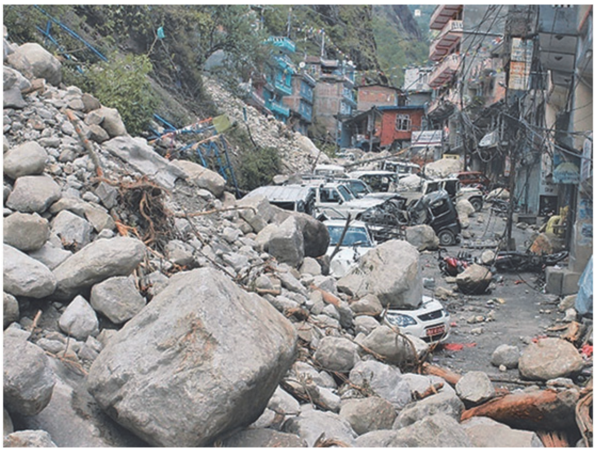

Photo. 2 Rock fall in Liping Bazar, near to Nepal-China border

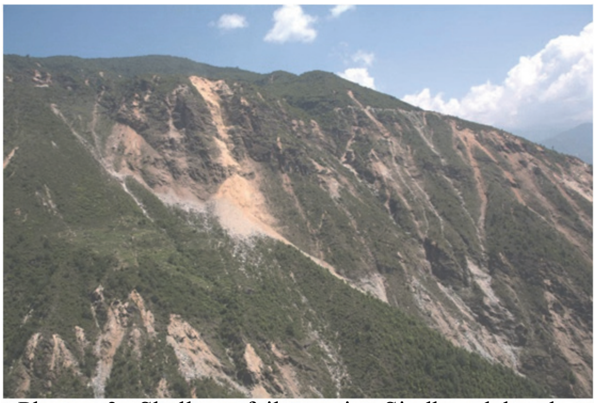

Photo. 3 Shallow failures in Sindhupalchowk district

Deep-seated landslide is was not much after the Gorkha Earthquake, but few failures are seen in old landslide mass (Photo 4) in the Rasuwa district, north of Kathmandu.

Debris flow and mud flow type of earthquake-induced landslide was not observed in the affected area due to dry season in the area, but rock fall triggered debris flow and avalanche was observed in the Langtang valley and killed more than 200 persons on the spot. The Langtang valley was vanished after this incident (Photo. 5).

Valley fill collapse was observed in many areas, especially on road. But in Kathmandu such failures were observed only on Kathmandu airport road and the road was damaged due to valley collapse (Photo. 6).

Photo. 4 Failure in deep-seated old landslide

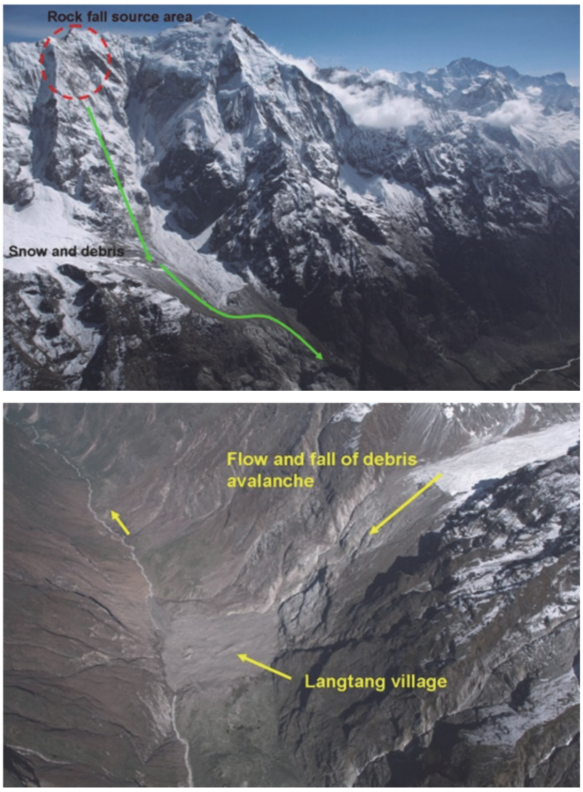

Photo. 5 Debris flow and avalanche in Langtang village, source area also is shown in photo.

Photo. 6 Valley fill collapse in the Kathmandu airport road.

Photo. 7 Failure in Cut-and-fill part of rural road

Cut-and-fill failures were very common in mountain roads in the affected area. Cut-and-fill land were also damaged in settlement area of Kathmandu (Photo 7).

6.2 Land subsidence in Kathmandu

The Gorkha Earthquake was destructive not only due to structural weakness of the construction but there were many problem of differential settlement of the ground. Field visit during rapid damage assessment in Kathmandu valley suggested that nearly 40% of damages were due to land subsidence. Similarly, land subsidence due to liquefaction of lower sandy strata was also another problems observed in various location of the Kathmandu valley (Photo. 8).

Photo. 8 Land subsidence and tilting of house due to liquefaction of lower strata

6.3 Liquefaction in Kathmandu

Along with land subsidence, a few sand boils were appeared in Kathmandu due to liquefaction of the lower strata (Photo 9). Although houses were not submerged inside the liquefied layer, but tilting and road collapse were appeared in many area of Kathmandu. Sand boils were appeared in southern part of the valley, mainly on the old river channel. The percentage of sand is very high in the sample taken from sand boil area (Fig. 6) shown in Photo 9.

7. Concluding remarks

This study evaluates features of the engineering geological issues in central Nepal after April 25, 2015 Gorkha Earthquake. In fact, this Gorkha Earthquake illustrates recent scenario of earthquake risk of whole Himalayan region. Primarily, this preliminary study concludes that the Nepal Himalaya has great risk of earthquake-induced slope failures. Especially many mountainous roads passing through the highly elevated Himalayan ridges as well as river valley are extensively damaged in this Gorkha Earthquake. Likewise, the lacustrine deposit of the capital city Kathmandu has shown different site response characteristic during the Gorkha Earthquake. Therefore, the behavior of the surface layer of lacustrine deposit as well as the layer underneath should be taken into consideration during seismic risk studies in the Kathmandu valley. Problem of liquefaction is well observed in the lacustrine sediment and river channel deposit. For the future planning of the Kathmandu city, liquefaction hazard needs to evaluate with recently developed geoscientific tools. Topographical effect on mountainous settlement during earthquake is another significant problem which need to response through suitable structural design of rural houses and other rural infrastructures.

Photo. 9 Sand boiling site at southern Kathmandu

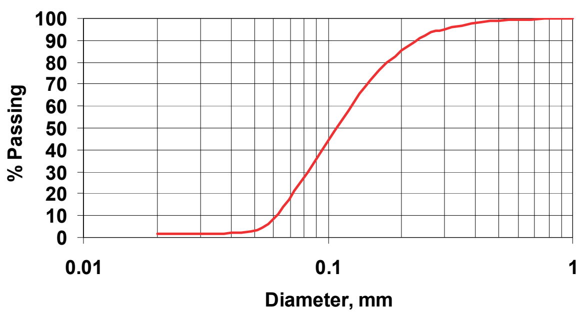

Fig 6 Grain size distribution curve of soil sample from sand boil

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References

Ambraseys, N. and Bilham, R. (2000): A note on the Kangra Ms = 7.8 earthquake of 4 April 1905, Current Science, Vol. 79, pp. 45-50.

Ambraseys, N. and Srbulov, M. (1995): Earthquake induced displacement of slopes. Soil Dyn. Earthqu. Eng, Vol. 14, pp. 59– 71.

Avouac, J.P., Bollinger, L., Lavé, J., Cattin, R. and Flouzat, M. (2001): Le cycle sismique en Himalaya, C R Acad Sci Vol. 333, pp. 513–529.

Dahal R.K., Bhandary N.P., Timilsina M., Yatabe R., and Hasegawa S. (2013): Earthquake Induced Landslides in the Roadside Slopes of East Nepal After Recent September 18, 2011, In Eds Ugai ,K., Yagi, H., Wakai, A., Earthquake Earthquake Induced Landslides, Springer Berlin Heidelberg, pp. 149-157.

Dahal, R.K., Hasegawa, S. (2008): Representative rainfall thresholds for landslides in the Nepal Himalaya, Geomorphology, Vol. 100, No. 3-4, pp. 429-443.

Gansser, A. (1964): Geology of the Himalayas, London Wiley Interscience, 289p.

Geli L., Bard P.Y., Jullien B. (1988): The effect of topography on earthquake ground motion: a review and new results, Bulletin of the Seismological Society of America, Vol. 78, No. 1, pp. 42-63.

Gilbert F. and Knopoff, L. (1960): Seismic Scattering from Topographic irregularities, Journal of Geophysical Research Vol. 65, pp. 3437-3444.

Hasegawa, S., Dahal, R.K., Yamanaka, M., Bhandary N. P., Yatabe R., and Inagaki H. (2009): Causes of large-scale landslides in the Lesser Himalaya of central Nepal, Environmental Geology, Vol. 57, No. 6, pp. 1423-1434.

IRIS (2015): Magnitude 7.8 NEPAL, Saturday, April 25, 2015 at 06:11:26 UTC, document available in http://www.iris.edu/hq/files/programs/education_and_outreach/retm/tm_150425_nepal/150425_Nepal.pdf (accessed on 2015/7/15).

Lin, C.-W., Shieh, C.-L., Yuan, B.-D., Shieh, Y.-C. Liu, S.-H. and Lee, S.-Y. (2003): Impact of Chi-Chi earthquake on the occurrence of landslides and debris flows: example from the Chenyulan River watershed, Nantou, Taiwan, Engineering Geology Vol. 71, pp. 49-61

Miles, S.B. and Keefer, D.K. (2000): Evaluation of seismic slope-performance models using a regional case study, Environmental & Engineering Geoscience, Vol. 6, No. 1, pp. 25-39

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 microtremor analysis, Earthq Eng & Eng Vib, Vol. 11, pp. 257-268.

Rai, S.M., Upreti, B.N., Guillot, S., Pêcher, A. and Fort, P.L. (2004): Mineral chemistry (biotite, muscovite, garnet, and plagioclase) in the Kathmandu and Gosainkund regions, central Nepal Himalaya, Journal of Nepal Geological Society Vol. 30, pp. 55-66.

Seeber, L. and Armbruster, J. (1981): Great detachment earthquakes along the Himalaya arc and long-term forecasting in earthquake prediction: An International Review, Maurice Ewing Series Vol. 4, pp. 259-279.

Uchida, T., Kataoka, S, Iwao, T., Matsuo, O., Terada, H., Nakano, Y., Sugiura, N. and Osanai, N. (2004): A study on methodology for assessing the potential of slope failures during earthquakes. Technical note of National Institute for Land and Infrastructure Management, 91p. (in Japanese with English summary)

USGS (2015): The April-May 2015 Nepal Earthquake Sequence, document available in http://earthquake.usgs.gov/learn/topics/Nepal_Slides.pdf (accessed on 2015/7/15).

Zurick, D., Pacheco, J., Shrestha, B. and Bajracharya, B. (2005): Atlas of the Himalaya, International Centre for Integrated Mountain Development (ICIMOD), 96p.