Preliminary Field Assessment of Sinkhole Damage in Pokhara, Nepal

Rama Mohan Pokhrel, *JSPS Post-Doctoral Research Fellow, Institute of Industrial Science, University of Tokyo, Tokyo, Japan; email: pokhrel@iis.u-tokyo.ac.jp*
Takashi Kiyota, *Associate Professor, Institute of Industrial Science, University of Tokyo, Tokyo, Japan; email: kiyota@iis.u-tokyo.ac.jp*
Reiko Kuwano, *Professor, Institute of Industrial Science, University of Tokyo, Tokyo, Japan; email: kuwano@iis.u-tokyo.ac.jp*
Gabriele Chiaro, *Lecturer, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand; formerly JSPS Post-Doctoral Research Fellow, Institute of Industrial Science, University of Tokyo, Tokyo, Japan; email: gabriele.chiaro@canterbury.ac.nz*
Toshihiko Katagiri, *Technical Director, Institute of Industrial Science, University of Tokyo, Tokyo, Japan; email: toshi@iis.u-tokyo.ac.jp*
Itsuro Arai, *Graduate Student, Institute of Industrial Science, University of Tokyo, Tokyo, Japan; email: itsuro@iis.u-tokyo.ac.jp*

ABSTRACT: *Since November 2013, numerous sinkholes have been forming in the Armala area of Pokhara Valley, Central Nepal, posing serious threat to local residents. In order to provide measures aimed at reducing sinkhole risk, investigations into the cause and features of the sinkholes are crucial. This paper presents early research results based on two damage surveys conducted in June 2014 and November 2014 in the Armala area. Comparison of photos, taken in the two surveys, clearly indicates not only the formation of new sinkholes, but also the re-activation of filled sinkholes. By means of dynamic cone penetration tests and surface wave method investigations, qualitative characterization of the soil profile was attained, and shallow weak soil layers which are believed to be the location for future sinkholes could be identified. On the basis of the field investigation results, possible sinkhole formation mechanisms are identified for the Armala area. Furthermore, results of a reconnaissance survey conducted in the Armala area in early May 2015 (following the 2015 Gorkha Nepal Earthquake, which occurred on April 25th) are also reported. Although the epicentral distance to Pokhara was closer than Kathmandu, which suffered from severe damage, no major apparent effects of the earthquake were observed in the sinkhole damaged area.*

KEYWORDS: sinkholes, site investigation, dynamic cone penetration test, surface wave method, Pokhara

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

Pokhara Valley is located in Central Nepal (Figure 1). Geologically, it is an intermontane basin filled with large quantities of quaternary deposits, including layered clastic deposits (gravel, silt and clay), brought from the Annapurna mountain range probably by a series of catastrophic debris flows (Yamanaka et al., 1982). Due to the presence of a large volume of calcareous material in the sediments, karst structures (e.g. subsurface flow channels, solution cavities, sinkholes etc.) are widely developed both at the surface and subsurface (Gautam et al. 2000). These structures are usually unpredictable and their effects can either lead to slow and gradual ground subsidence or to sudden catastrophic collapse known as sinkholes (Zhou and Beak, 2011). The main problem associated with sinkholes (already collapsed or not) is that they pose a serious threat to structures and infrastructure such as roads etc., as well as agricultural farmland. An example of Karst-related destruction in the Pokhara Valley is the collapse of a highway bridge over the Seti River (Dhital and Giri, 1993).

Submitted: 31 July 2015; Published: 10 December 2015
Reference: Pokhrel R.M., Kiyota T., Kuwano R., Chiaro G., Katagiri T. and Arai I. (2015). *Preliminary Field Assessment of sinkhole damage in Pokhara, Nepal*. International Journal of Geoengineering Case histories, http://casehistories.geoengineer.org, Vol.3, Issue 2, p.113-125. doi: 10.4417/IJGCH-03-02-04

In the North-Eastern part of Pokhara Valley, in the rural Armala area (Figure 1), since November 2013, the unforeseen formation of a significant number of sinkholes has been observed. Although some old sinkholes and caves are commonly found in the Pokhara Valley landscape, the recent and frequent sinkhole development within the Armala area clearly indicates that an accelerated sinkhole formation process is taking place, which obviously poses a serious threat to inhabitants and greatly affects the local economy, which essentially depends on agriculture.

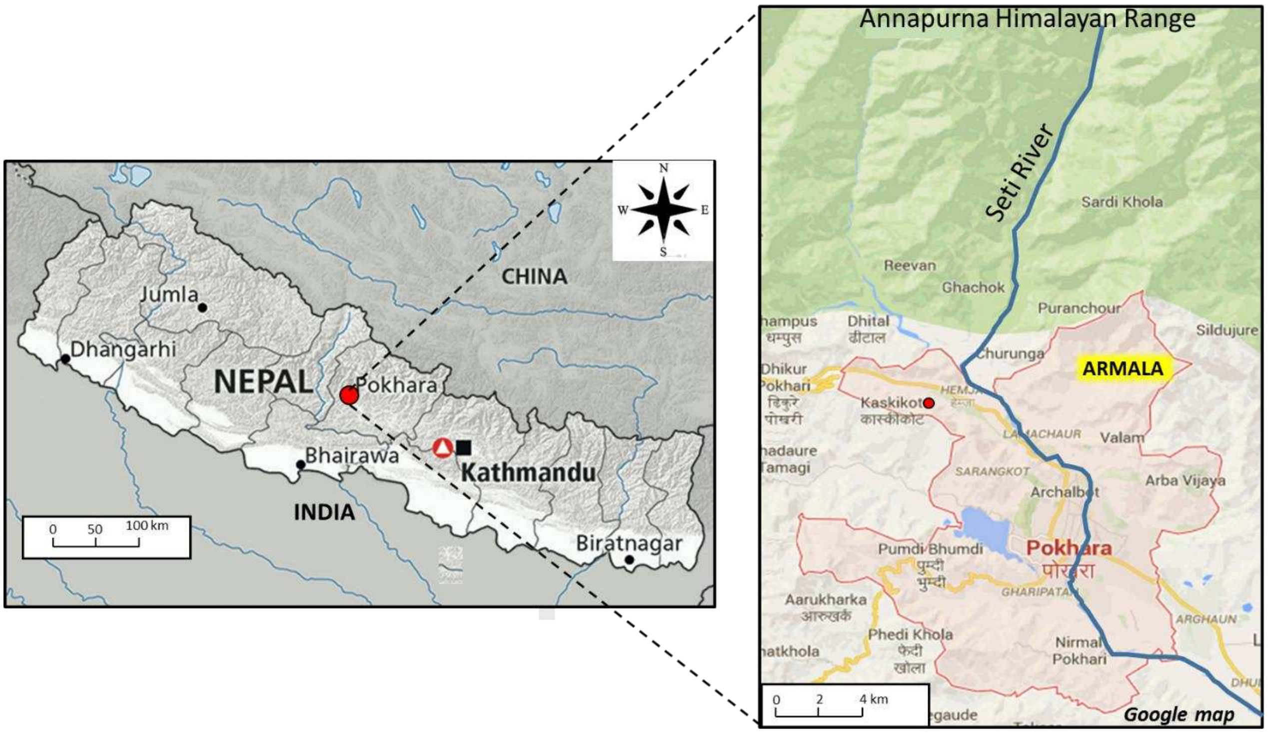


Figure 1. Location of Armala area in Pokhara Valley, Central Nepal.

Despite the great number of sinkholes formed and related socio-economic issues raised, the local authorities were able to only adopt a simple and quick solution consisting of the backfilling of the sinkholes. This choice was essentially driven by the lack of information regarding the cause of the sinkhole formation process. It is obvious that, such solution was not adequate and indeed more rational, definitive and effective countermeasures need to be considered. With the objective to gain a better understanding about the sinkhole development in the Armala area, a survey team of the University of Tokyo visited the damaged area in June 2014 and November 2014. As described in this paper, the major tasks of the survey team were: i) characterize the subsoil profile and acquire geotechnical properties for each soil layer identified; ii) create a database on the spatial distribution, chronology and features of existing sinkholes; iii) identify existing, but still hidden, cavities in the subsoil, i.e. the possible location of future sinkhole formation; iv) understand the possible mechanisms for such sinkhole formation; and v) provide suitable and effective engineering solution to minimize the damage caused by such a geo-hazard. This paper briefly reports on the preliminary field observations and geotechnical and geophysical in-situ investigations conducted during the two surveys and discusses the possible mechanisms for the sinkhole formation process in the Armala area. As well, results of a reconnaissance survey carried out in the Armala area in early May 2015 following the Gorkha Earthquake (Mw = 7.8) that struck Nepal on April 25, 2015 (Goda et al., 2015; Chiaro et al., 2015) are also briefly reported for completeness.

STUDY AREA AND OBSERVATION OF SINKHOLES

A detailed map of the study area reporting the location of sinkholes observed in June and November 2014, photo points and field investigations are shown in Figure 2. Topographically, the study area is a low-elevated zone as shown by the bird's eye view presented in Figure 3. This 3D image was obtained by overlapping LiDAR scanning carried out at three different locations (i.e. LS-1, LS-2 and LS-3 reported in Figure 2). There is a very gentle slope in the south-east direction, while a steep slope can be noticed in the north-west part. The black zones enclosed within circles are interconnected sinkholes as observed in November 2014.

The subsurface of the study area is essentially formed by lime dominated quaternary deposits, which are water soluble. Pokhara Valley is the area with the highest precipitation in Nepal and there are many opportunities for large amounts of water to easily seep in the ground during the rainy season (from June to August). In addition, the study area is an agricultural land, where recharge from the irrigated water is inevitable. This environment is the most favourable for sinkholes.

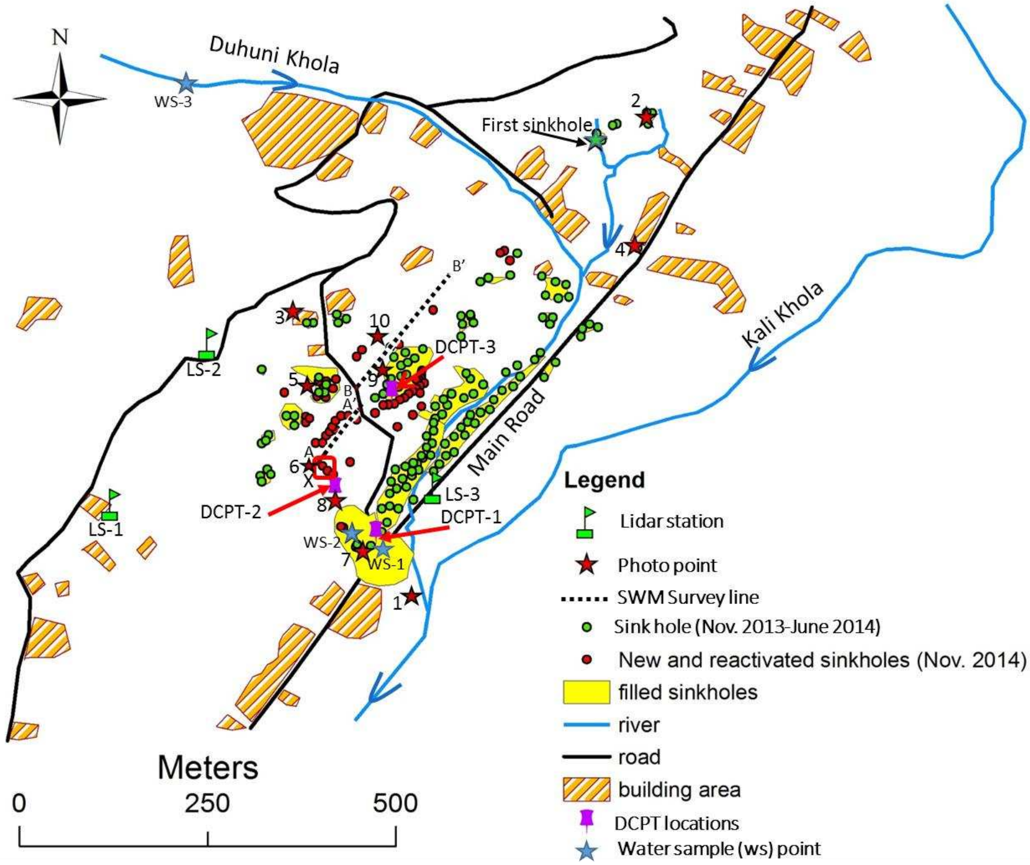


Figure 2. Detailed map of the sinkhole damaged area in Armala.

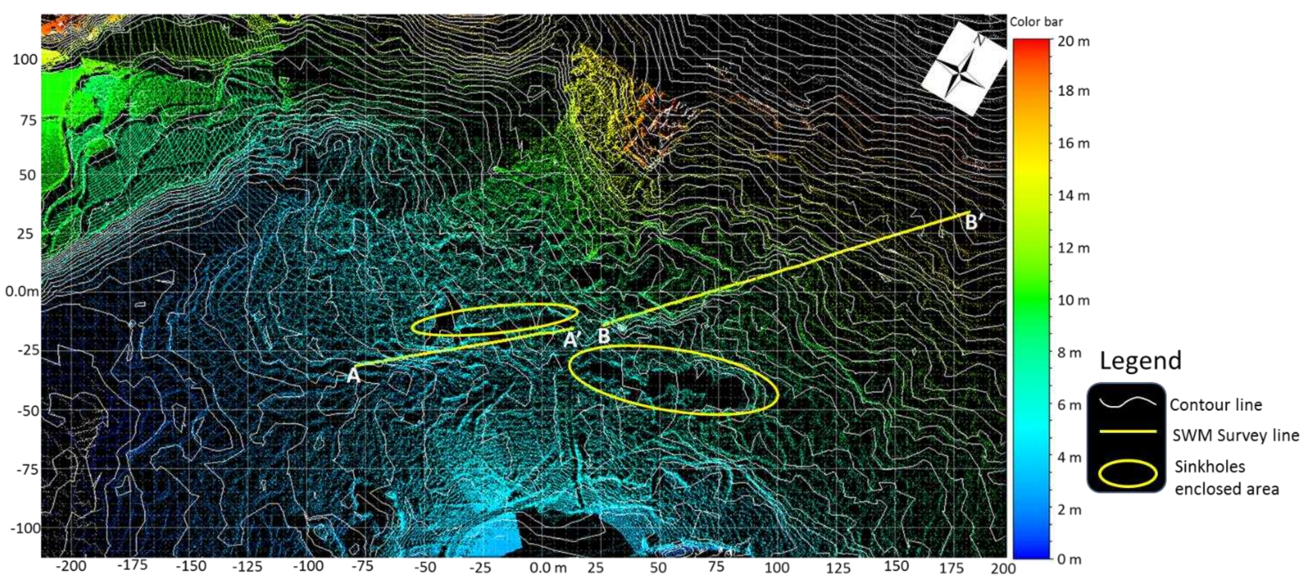


Figure 3. Bird's eye view of the sinkhole effected area.

Sinkholes Formed From November 2013 to June 2014

According to local residents, a muddy silty water outlet (shown in Figure 4 corresponding to photo point 1) was observed at the Kali Khola (Small River) riverbank about a week before the first sinkhole appeared in November 2013 (Figure 2). Since then, more than 150 sinkholes developed in this area until June 2014 and more than 200 sinkholes were reported up to November 2014.

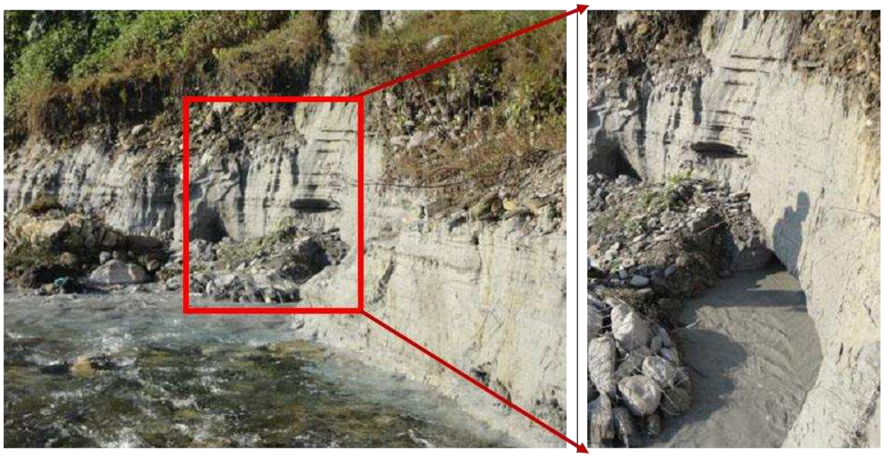


Figure 4. Muddy silty water outlet at the riverbank of the Kali Khola (photo point 1) (Photo Courtesy: Technical Research Team, 2014).

Typical circular-shaped sinkholes that appeared in November 2013 are shown in Figure 5(a). Although the first sinkhole appeared in the northern part of the investigation site, the majority of the sinkholes actually were formed along the Duhuni Khola nearby the main road (as shown by the green dots in Figure 2) between November 25th and December 5th 2013. Later on, the formation of sinkhole extended towards the western side. The depth and size of the sinkholes on level ground along Duhuni Khola were bigger than those developed on sloped ground and increased with time. Eventually, large-size sinkholes ended to connect each other along the Duhuni Khola.

Figure 5. (a) Typical sinkholes formed in November 2013 (Photo Curtesy: Keshab Sharma); and (b) a sinkhole formed in June 2014 (photo point 2).

Figure 5(b) shows a small sinkhole that appeared, at photo point 2, just one day before the survey team visited the damaged area in June 2014. Note that although the sinkhole in Figure 5(b) has a small diameter at the surface, its diameter is in reality much larger in the subsurface (as indicated by the red dashed line). Such spherical shape is due to the fact that the soil in the upper part of the sinkhole was retained by the grass root system supporting the surface soil.

During the June 2014 survey, the trace of a number of sinkholes previously formed since November 2013 could be typically observed in both sides of the Duhuni Khola (green dots in Figure 2). All the sinkholes were completely back filled, except for the sinkholes at photo points 7 and 8 (see also Figures 10 and 11). Originally, they had a diameter of about 10m and a depth of about 7 m. However, at the time of the survey, the upper part was already partially filled by sediments, and the measured depth was less than 4 m.

The sinkholes affected not only agricultural farmland. They also caused the collapse of manmade structures like the cowshed shown in Figure 6(a) (corresponding to photo point 3), and the masonry kitchen shown in Figure 6(b) (corresponding to photo point 4). The homeowner reported that about 60 m^3 of filling material were used to fill the sinkhole shown in Figure 6(a).

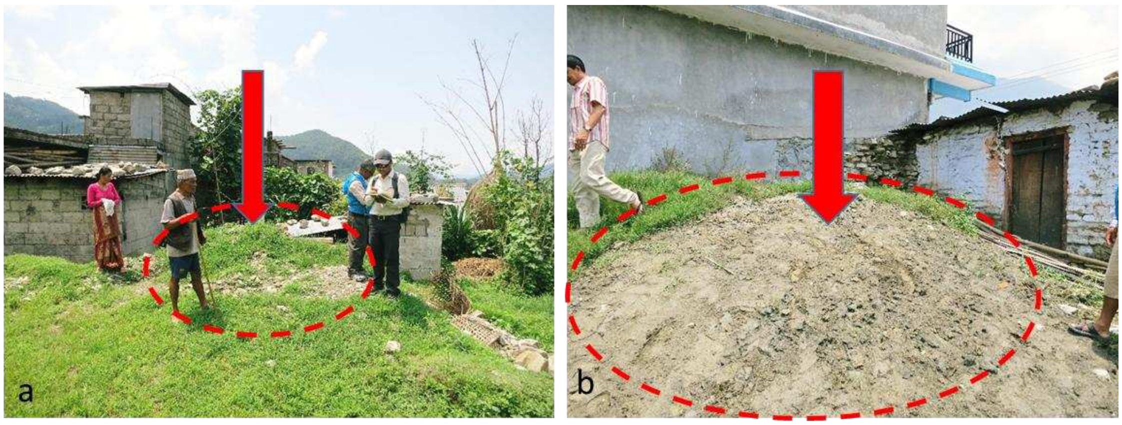


Figure 6. Typical effects of sinkhole formation on residential properties observed on June 2014 included the collapsed of (a) a cowshed and (b) a masonry kitchen.

Sinkholes Formed Between July 2014 and November 2014

During the November 2014 survey, a number of sinkholes of recent formation (known to have formed in August 2014) were mostly observed in the west side of the surveyed area. In the map shown in Figure 2, it can be seen that the new sinkholes (shown as red dots) are concentrated on the western side of the old sinkholes. Some of the new sinkholes may be old sinkholes re-activated during the rainy season in 2014.

Immediately after the occurrence of the sinkholes, a wide area affected by the cave-in was backfilled by using gravelly soil retrieved from nearby quarries, which is identified by a yellow color filled area in Figure 2. Though, at the time of the first damage survey in June 2014, most of the sinkholes had been fully backfilled (Figure 7a corresponding to photo point 5), the photos taken in November 2014 at the same location clearly show that the backfilling was not an adequate solution as most of the former sinkholes were re-activated (Figure 7b) likely in August 2014 during the peak rainy season in Pokhara Valley.

Figure 7. (a) Sinkholes backfilled area (photo point 5) as seen in June 2014; and (b) Re-activated sinkholes as observed in November 2014.

Among many, sinkholes N1, N2 and N3 in the area X shown in Figure 2 were found to be of particular interest. They were developed in a delimited area of approximately 10 m × 20 m, as shown in the schematic map shown in Figure 8. They have a circular pattern and diameters ranging from 4.6 m (N3) to 6.8 m (N1). Their depth measured at the top of the collapsed soil varied from 2.2 m (N1, N3) to a maximum of 3.5 m (N2). According to witnesses, N1 was the first sinkhole to be formed. A few days later, N2 caved-in and finally N3 developed. This progressive formation of several sinkholes along a straight line (moving along the uphill direction from N1 to N3) may suggest that the collapse of N1 caused the complete disruption of underground water flow. Consequently, water started to erode the soil just adjacent to N1 until a new cave-in (N2) was formed. In a similar way, N3 was later developed. The same pattern of sinkhole formation occurred often since November 2013. Most of the newly developed sinkholes are located on the upstream side of the underground water flow.

As mentioned earlier, as an immediate mitigation work, all the old sinkholes were filled by the local government. This practice could disrupt the underground water flow so that ultimately the caving process caused the re-activation of sinkholes. Note that due to loose conditions of backfilled material, it is expected that the development of a re-activated sinkhole is much quicker than that of the original sinkhole where natural compacted soils was gradually eroded by water.

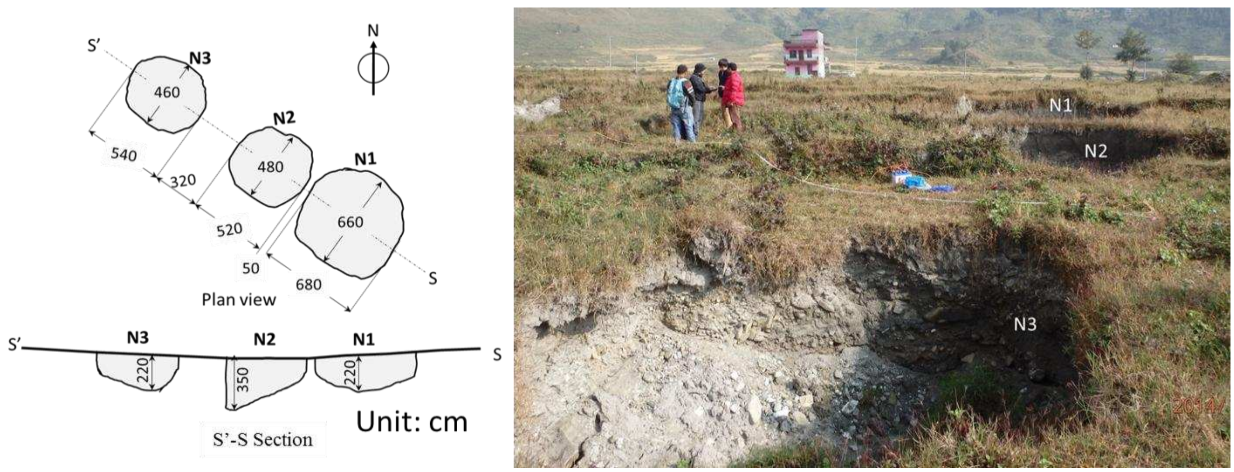


Figure 8. Series of sinkholes appeared in the area X in Figure 2 (photo point 6).

The Effects of the 2015 Gorkha, Nepal Earthquake in the Armala Area

On April 25th 2015, the Central part of Nepal was hit by an earthquake with moment magnitude 7.8 (USGS, 2015). Widespread damage was observed across many Districts of Nepal, including not only mountainous areas near the epicentral area but also the Kathmandu Valley (Goda et al. 2015; Chiaro et al., 2015). Pokhara Valley is located approximately 70 km southwest of the epicentral area. According to USGS the ground shaking in Pokhara Valley was not as severe compared to the Kathmandu Valley.

Figure 9. Muddy silty water observed in the sinkhole damaged area (photo point 7) following the 2015 Gorkha Nepal Earthquake.

Following the earthquake, muddy water was observed at the outlet of the local spring (Figure 9) in the Armala area (photo point 7), indicating that the earthquake had altered the subsoil conditions in some ways. Nevertheless, a field survey confirmed that no new sinkholes were formed and the size of existing sinkholes did not change. Yet, as mentioned earlier, muddy water indicates a high content of silt and fines in the water, and thus a process of erosion occurring in the subsoil. The earthquake may have induced a change in groundwater level and/or an increase of pore pressure that re-activated the erosion process. For this reason, the formation of new sinkholes may be anticipated in the near future, especially during the rainy season.

FIELD INVESTIGATION

A major challenge faced in this sinkhole damage survey was the identification and delineation of underground cavities. Usually, geological and geomorphological methods are used to map probable sinkholes. Yet, they are not adequate for the detection and precise location of cavities. The problem becomes more complex in such an area where the presence of natural cavities is not known. In such a case, to identify the location of cavities in the subsurface as well as the presence of subsurface channels, geophysical methods are more suitable. With this goal in mind, dynamic cone penetration tests (DCPTs) and surface wave methods were performed as described hereafter.

Dynamic Cone Penetration Tests (DCPTs)

In June 2014, DCPTs were carried out at three different locations within the damaged area (Figure 2). The objective of these tests was to determine the thickness of the cavity-bearing formation and bearing capacity of the layers. In the portable DCPT test a rod with a 60^0 cone tip is driven into the soil by a drop hammer of 5kg mass free falling through a height of 50cm. The number of hammer blows required to drive each 10cm of rod is recorded. This number of hammer blows is converted as N_d value by using equation 1 (JGS, 2013).

$$N_d = \frac{100 \times N}{\Delta h} \tag{1}$$

where, N is number of blow and Δh is a depth of penetration, usually 10 cm.
The obtained N_d value is plotted in the graph against depth. The lower N_d values indicate a loose soil layer and the higher N_d values correspond to a compacted soil or stiff soil.

DCPT-1 was carried out at the bottom of a non-filled sinkhole as shown in Figure 10 (corresponding to photo point 7 in Figure 2). As already mentioned, this area is composed of recent flood plain deposits, including a thick gravel layer at shallow depth. Thus, DCPTs could not penetrate more than 6.55m. However, the test results would suggest that the probable depth of the sinkholes should be approximately 4.5-5m, or more precisely 6.5-7 m below the ground level considering that the actual ground level was approximately 2m above the sinkhole bottom.

Figure 10. Result of the Dynamic Cone Penetration Test at DCPT no. 1 at the bottom of a sinkhole.

On the other hand, DCPT-2 (Figure 11) was carried out just adjacent to the sinkhole at photo point 8 in Figure 2. The test results were correlated with stratigraphy and structure of the deposits (Figure 11). The converted DCPT N_d-values are plotted in Figure 11. The upper layers of the surface soil could be penetrated until reaching a layer of gravel at a depth of 2.4 m, where even by hitting more than 150 times the penetration process stopped.

DCPT-3 was carried out at the top of the filled material at photo point 9. As shown in Fig. 12a and 12b, the testing location disappeared due to the collapse of filled material during the rainy season between June and November 2014. From the test results shown in Fig. 13, it is concluded that the used filling materials are sand and gravelly soils. However, the compaction at the surface is not good enough because the N_d-value measurement is low. The DCPT results suggest that the cavity bearing formation is below the gravel layer, and then progressively the cavity size increased and finally the loose upper layer collapsed.

By comparing the N_d -values obtained from DCPT-2 and DCPT-3, it is noted that the filled materials are looser than the natural soil. Therefore, the filled material can be easily caved-in and induce the re-activation of filled sinkholes during the rainy season.

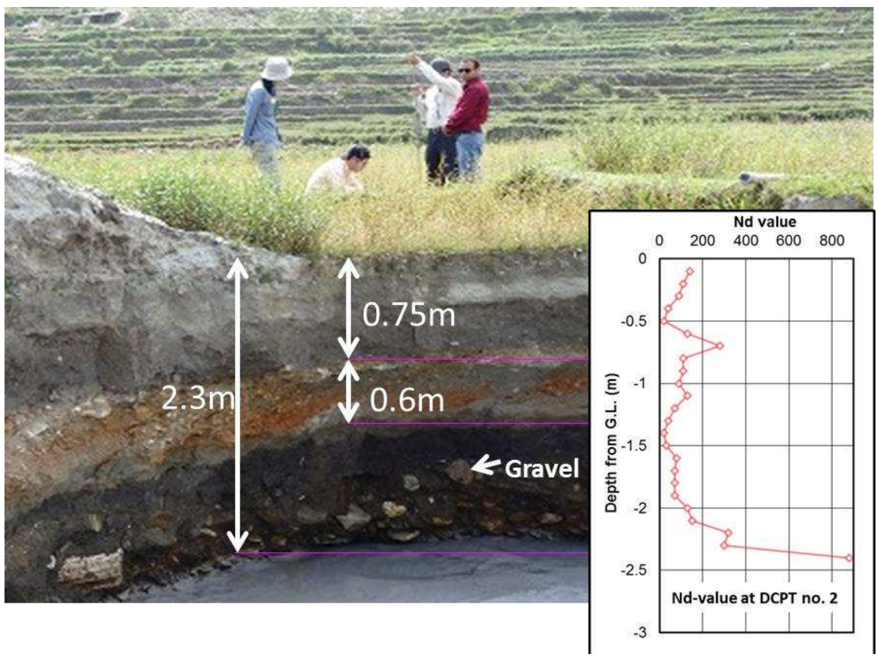


Figure 11. Soil profile and DCPT result at DCPT-2 obtained for the sinkhole in photo point 8 (Photo in June 2014).

Figure 12. a) Dynamic Cone Penetration Test at DCPT no. 3 (photo point 10) on the filled material (photo taken in June 2014) and b) re-activated sinkhole at the same location (photo taken in November 2014).

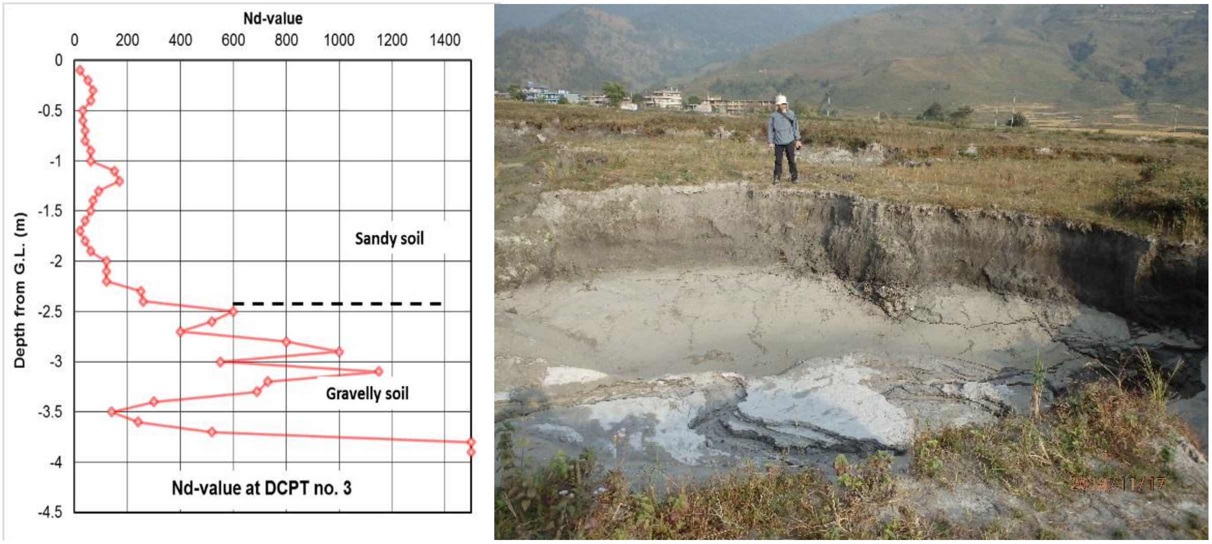


Figure 13 (a) Result of DCPT 3 conducted in June 2014 and (b) its location collapsed after the test.

Surface Wave Method (SWM)

SWM is a non-destructive geophysical method widely used to investigate subsurface structures. Depending on the behaviour of natural cavities and associated fracturing, SWM may provide fairly distinct geophysical contrasts with the surrounding country rocks at roughly two or more diameters from the cavity (Bishop et al., 1997). In this method, near surface problems are studied by using the dispersive character of Rayleigh waves, which are then converted into shear wave velocity measurements. This method captures both the horizontal and vertical variation of elastic properties of the material.

SWM surveys were performed along the two sections A-A' and B-B' shown in Figure 2 and Figure 3. The total length of the survey was 263 m (i.e. 95 m along the section A-A' and 168 m along the section B-B'). The testing conditions consisted of 24 vertical-component geo-phones (Figure 14) placed at 1m interval while ensuring good contact with soil. A 5 kg hammer was used to generate surface waves by impacting vertically on a rubber plate. The source was also positioned at 1m interval, to be precise at 0.5 m between two subsequent geophones.

After finishing one 24 m profile, the subsequent measurement was made with at least 3 geophones overlapping. The nearest source to the receiver offset was 0.5 m. An OYO MCSEIS-SW was used for data acquisition. Figure 14 shows the typical surface wave method alignment used in this investigation.

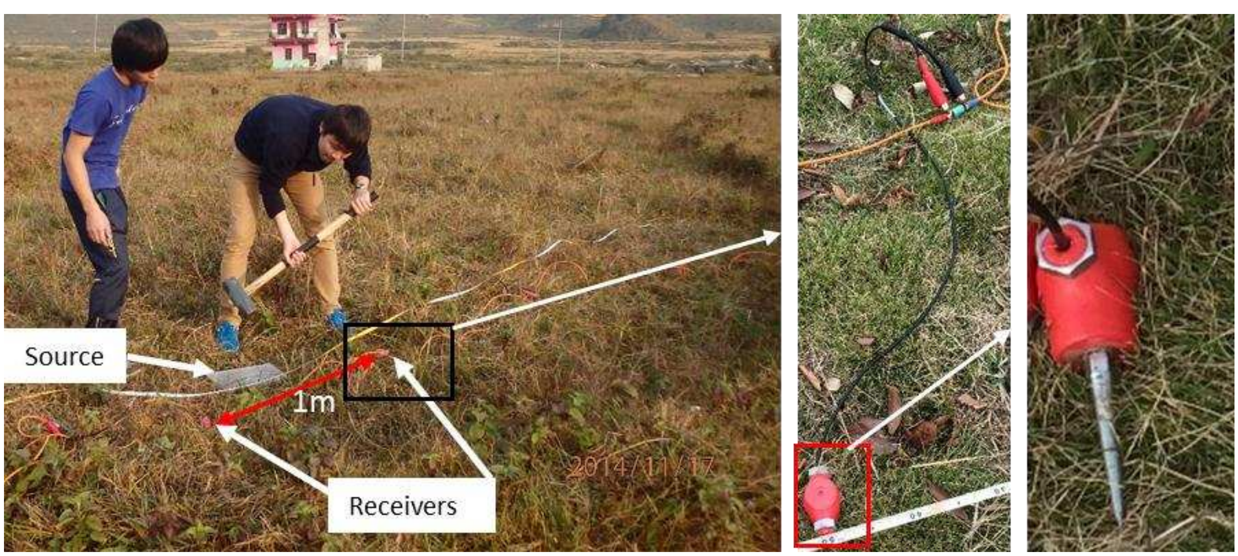
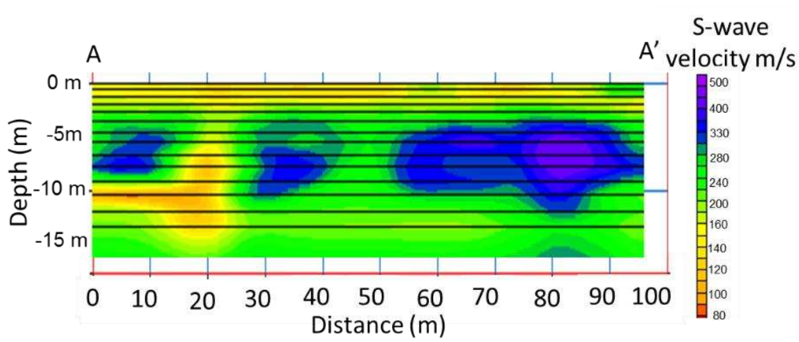
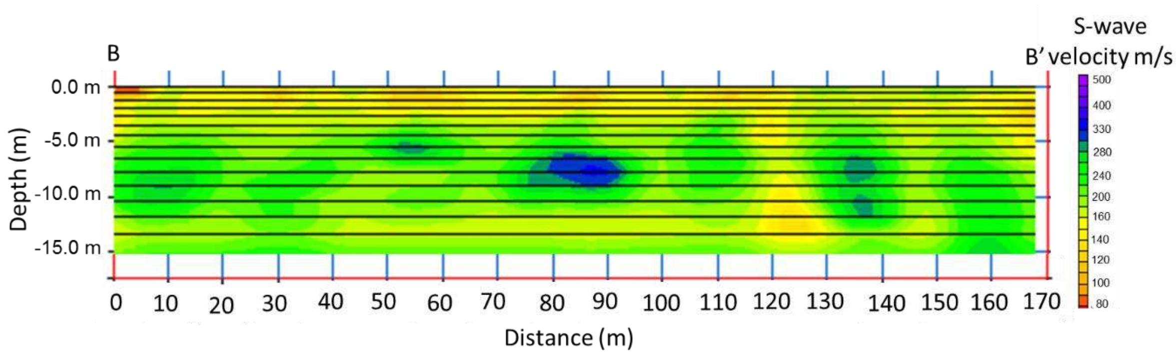


Figure 14. Surface wave method used in this investigation.

The results of SWM test along sections A-A' and B-B' are shown in Figure 15. It can be seen that the shear wave velocity for the surface layer is in the range of 100-160 m/s, confirming the presence of a loose sand layer of 1.5-m thickness. The underlying gravel has a higher velocity than the surface layer with a shear wave velocity of about 240 m/s. Moreover, the stiff soil below 4 m depth has a shear wave velocity greater than 300 m/s. The velocity of the layer around 10 m depth denotes water flowing path and loose material. A low velocity section observed 20 m far from the starting point in profile A-A' indicates possible cavities in the ground. Similarly, in profile B-B' the loose material at a depth of about 12 m indicates a possible water flowing layer and the weak strata between 120 m to 130 m is a possible future sinkhole.



a



b

Figure 15. Profiles of surface wave method: (a) section A-A'; and (b) section B-B'.

POSSIBLE MECHANISMS OF SINKHOLES IN ARMALA AREA

The subsurface geology of the Armala area is essentially formed by loose silt containing lime, which was deposited by the Seti River flowing through the central part of the Pokhara Valley (Figure 1). Similarly, the surface geology is formed by recent alluvial deposit carried by the Kali Khola flowing north to south along the eastern side of the study area (Figure 2). Chemically, it contains CaO (35%) and MgO (2%) (Technical Research Report, 2014). As a result, the main characteristic of this loose silt is that it easily dissolves in water. The latter process is currently happening in the damaged area, where surface water seepage ultimately saturated the calcareous silty material.

The groundwater flow is the triggering factor involved in the generation of sinkholes observed in this study. In fact, it is assumed that in the Armala area, there has been an active erosion process (probably lasting hundreds of years), where water gradually dissolved soluble soil, creating cavities beneath the ground surface (Figure 16a). However, such cavities were stable and likely small in size. In fact, despite the high sinkhole risk, the formation of sinkholes was rarely observed in past decades in the Armala area.

Nevertheless, in November 2013, suddenly, a water spring was observed for the first time by local residents (Figure 4). It was rapidly followed by the formation of a number of sinkholes, as already described previously. The authors believe that the formation of the water spring induced a change in the groundwater level i.e. water table decline (Figure 16(b)). The drastic fall in groundwater level and its fluctuation during rainy season, accelerated the erosion process (as evidenced by muddy water observed at the water spring outlet) and cavity enlargement (Figure 16 (c)). The evidence of the erosion process in the ground is shown in Figure 17. The water sample collected from different points in the study area in June 2014 has different turbidity. The water sample collected at the stream or seepage location (water sample (WS) point 3 in

Figure 2) is clear and has no sediments. On the other hand, water samples collected at WS point 1 and 2 shows high turbidity (Figure 17). This indicates that underground water continues to dissolve the silt and there was a continuous caving process till June 2014. As the process continued, the loose, unconsolidated soil and sand above was gradually washed into the cracks and voids. Depending on how thick and strong the top layer was and how close to the surface the void beneath was, the ground was not able to sustain its own weight. Thus, cavities that before were stable, suddenly became unstable and collapsed (Figure 16(d)).

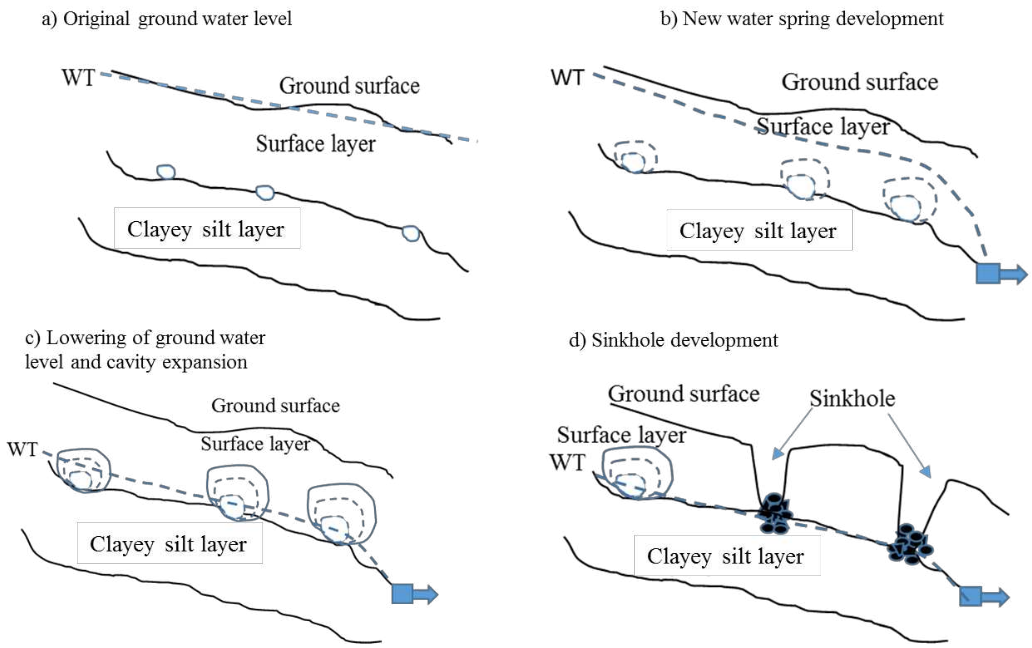


Figure 16. Probable mechanisms of sinkhole observed in the Armala area.

Figure 17. Turbidity of sampled water collected at different point in the Armala area in June 2014 (the water sample locations at ws1, ws2 and ws3 respectively in Figure 2).

MITIGATION MEASURES AIMED AT REDUCING SINKHOLE RISK

On the basis of this preliminary survey and investigation, as a mitigation process, various recommendations were made to local residents and authorities. At the time of the first visit to the Armala area in June 2014, the authors strongly suggested to local authorities to review the land use planning and regulation of the area and particularly inhibit irrigation in this area, and evacuate buildings located very close to the damaged sinkhole zone.

It is known that the selection and application of mitigation measures aimed at reducing sinkhole risk generally require the identification of the existing sinkholes and the delineation of the areas where future sinkholes are likely to occur. It is crucial to collect information on the size and frequency of the sinkhole events, and on the mechanisms and rate of formation (Gutierrez et al., 2008). Therefore, at the time of the second visit in November 2014, the authors performed geophysical surveys to identify the cause and mechanisms of sinkholes observed in the Armala area. On this basis, suitable engineering countermeasures aimed at diminishing sinkhole risk are now being considered, such as:

- prevent irrigation;
- using an effective drainage system and diverting surface runoff;
- remediating existing sinkholes and clogging shallow holes;
- identifying cavities in the soil and filling them by grouting;
- improving the ground by compaction or ground injection to increase the strength and bearing capacity of the soils.

SUMMARY

Since November 2013, the unpredictable formation of a significant number of sinkholes has been observed in the Armala area, Pokhara Valley (Nepal), posing enormous risk to people residing in the affected area. The Authors conducted sinkhole damage surveys in the Armala area to investigate the formation of such sinkholes and identify the location of hidden cavities that could develop new sinkholes. The results from the survey can be summarized as follows:

1. A number of sinkholes developed in a recent fluvial deposit, which is very soft and calcareous in nature. A sudden decline of groundwater table is likely the triggering factor involved in the generation of the sinkholes observed in this study;
2. Sinkholes caused severe damage to residential properties, roads, crops, land etc. However, there are still many hidden cavities that likely will generate new sinkholes, since the erosion process is still occurring;
3. As a possible countermeasure, the government agency backfilled a number of sinkholes. However, it was clearly a temporary and not adequate solution since the majority of the sinkholes re-activated during the rainy season;
4. The results of the DCPTs and surface wave method show that there is a loose layer laying on top of a gravelly layer. Below this gravelly layer there is a very stiff clayey silt layer, which is water soluble in nature and is considered as the sinkhole formation layer.

ACKNOWLEDGEMENTS

The Japan Society for the Promotion of Science (JSPS) is greatly appreciated for funding the first and fourth authors' research fellowship in Japan. Financial support by the JSPS KAKENHI Grant Number 15H02631 is greatly acknowledged. Mr. Tomoharu Mera (former graduate student of the University of Tokyo), Mr. Yohei Koike (former graduate student of Yokohama National University) and Pradeep Pokhrel (graduate student of Institute of Engineering, Tribhuvan University, Kathmandu, Nepal), are gratefully acknowledged for their help in the field work and data acquisition. The authors would also like to thank Dr. Laura Banasiak for her valuable suggestions to improve the manuscript.

REFERENCES

Bishop, I., Styles, P., Emsley, S.J., Ferguson, N.S., (1997). "The detection of cavities using the microgravity technique: case histories from mining and karstic environments." Modern Geophysics in Engineering Geology. Geological society, Engineering Geology Special Publication 12, pp. 153-166.

Chiaro, G., Kiyota, T., Pokhrel, R.M., Gods, K., Katagiri, T. and Sharma, K., (2015). "Reconnaissance report on geotechnical and structural damage caused by the 2015 Gorkha Earthquake, Nepal." Soils and Foundations, 55(5), doi:10.1016/j.sandf.2015.09.006.

Dhital, M.R. and Giri, S., (1993). "Engineering-geological investigations at collapsed the Seti Bridge site, Pokhara." Bulletin Department of Geology, Tribhuvan University, 3 (1), 119-141.

Gautam, P., Pant, S. R., and Ando, H., (2000). "Mapping of subsurface karst structure with gamma ray and electrical resistivity profiles: a case study from Pokhara valley, central Nepal." Journal of Applied Geophysics, 45(2); 97-110.

Goda, K., Kiyota, T., Pokhrel, R.M., Chiaro, G., Katagiri, T., Sharna, K., Wilkinson, S., (2015). "The 2015 Gorkha Nepal Earthquake: insights from earthquake damage survey." Frontiers in Built Environment, 1(8), 1-15, doi: 10.3389/fbuil.2015.00008.

Gutierrez, F., Copper, A.H. and Johnson, K.S., (2008). "Identification, prediction and mitigation of sinkhole hazards in evaporate karst areas." Environmental Geology, 53:1007-1022. DOI 10.1007/s00254-007-0728-4.

Japanese Geotechnical Society, (2013). “Method for portable dynamic cone penetration test” Japanese Standards and explanations of Geotechnical and Geoenvironmental Investigation Methods, A standard number JGS 1433-2012. pp. 317-318

Pokhrel, R.M., Kiyota, T., Kuwano, R., Chiaro, G., Katagiri, T., (2015). “Site investigation of sinkhole damage in the Armala area, Pokhara, Nepal.” Proceedings of the International Conference on Geotechnical Engineering, Colombo, Sri Lanka, pp. 109-112

Technical Research Team (2014). “Technical research report of ground subsidence at Jaimure phant, Aramala V.D.C., Kaski District.” Technical Report, Pokhara, Kaski.

Yamanaka, H., Yoshida, M. and Arita, K., (1982). “Terrace landform and Quaternary deposits around Pokhara valley, Central Nepal.” Journal of Nepal Geological Society, 2, 95-112.

USGS, (2015): http://earthquake.usgs.gov/realtime/product/finite-fault/us20002926/us/1429969841288/20002926.html (accessed on 23 May 2015).

Zhou, W. and Beck, B. F., (2011). “Engineering issues on Karst.” In Karst management, Springer, Tampa, USA, 9-45.