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SINKHOLE DAMAGE IN ARMALA AREA IN POKHARA, NEPAL: A PRELIMINARY SURVEY REPORT

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ABSTRACT: Nepal is a seismic prone country. There is a very high potential that an upcoming strong earthquake may have catastrophic consequences in Armala area, Pokhara Valley, where the unexpected formation of a substantial number of sinkholes is already in place since November 2013. In order to provide measures aimed at reducing sinkhole risk, new insights into the sinkhole cause and features is crucial. This paper reports on two damage surveys conducted in June and November 2014 by the Authors in Armala area, to investigate the cause of such sinkholes. Comparison of photos, taken in the two surveys, clearly indicates not only the formation of new sinkholes, but also the re-activation of sinkholes that were previously backfilled. By means of S-wave explorations and dynamic cone penetration tests, qualitative characterization of soil profile was attained and shallow weak soil layers, which are believed to be the location for future sinkholes, could be identified. Sinkhole cause are described and feasible countermeasures are proposed to mitigate sinkhole risk in Armala area.

Key Words: Sinkholes, Site investigation, Dynamic cone penetration test, Surface wave exploration, Pokhara

INTRODUCTION

Since November 2013, the unpredicted formation of a significant number of sinkholes has been observed in Armala area, Pokhara Valley (Nepal) (Figure 1). Sinkholes are common naturally occurring geological feature. However, in the case of Armala area, their abrupt development and increasing frequency pose hazards to approximately 70 households. Geologically, the Pokhara valley 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 series of catastrophic debris flows (Yamanaka et al., 1982). Due to the presence of large volume of calcareous material in the sediments, karst structures (subsurface flow channels, solution cavities, sinkholes etc.) are widely developed both at the surface and subsurface (Gautam et al. 2000). The main problem associated with sinkholes (already collapsed or not) is that they pose serious threat to properties like buildings, agricultural farmland, roads, etc. An example of Karst-related destruction in Pokhara valley is the collapse of a highway bridge over the Seti River (Dhital and Giri, 1993).

Although old sinkholes are commonly found in the landform in Pokhara valley, the recent and frequent sinkhole development within Armala area shows that an accelerated sinkhole formation

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process is taking place. In addition, Nepal is a seismic prone country and the risk it faces from earthquakes is very high (Figure 2). Historical records have shown that Nepal can expect two earthquakes of magnitude 7.5-8 on the Richter scale every forty years and one earthquake of magnitude of 8+ in Richter scale every eighty years. As shown in Figure 2, there are many parallel and sub-parallel thrusts extending from east to west of the country which can generates earthquake in Nepal. Consequently, there is a very high potential that an upcoming strong earthquake may produce catastrophic effects in the Armala area. In fact, it could cause the development of a significant number of large sinkholes in a wide area providing enormous risk to people residing in Armala area.

Figure 1 A google map showing location of Armala area (red circle) in Pokhara City

Therefore, it is crucial not only to understand the cause of the sinkhole formation in Armala, but also to provide effective countermeasures and identify existing but still hidden cavities in the subsoil as soon as possible in order to minimize the effects of such geo-disaster.

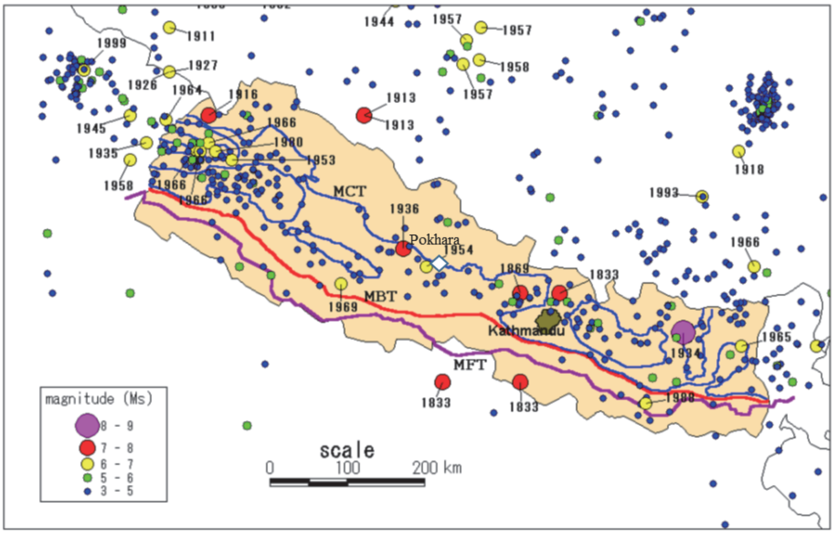

Figure 2 Epicentral distribution around Nepal from 1255 to 2001 (source: DMG, Nepal)

A team from the University of Tokyo, composed by the Authors, visited the damaged area in June and November 2014 to investigate about the cause of such natural disaster. This paper briefly reports on the field observations and geotechnical in-situ investigations conducted to characterise the soil profile and evaluate possible location for future sinkhole formation.

SINKHOLES

The Armala area is essentially formed by silt containing lime, which was deposited by the Seti River flowing through the Annapurna range. Chemically, it generally contains CaO = 35% and MgO = 2% (Technical Research Report, 2014). As result, the main characteristic of this loose silt is that it easily dissolves in the water. In the damaged area, the surface water seepage ultimately saturated the calcareous silty material, which was dissolved in the water.

The muddy silty water outlet (Figure 3) at the Kali Khola (Small River) riverbank (at point B red square in Figure 4) is the evidence that there are in act of erosion and cave-in processes within the subsurface of the damaged area. The local residence observed this muddy water outlet about one week before the first sinkhole appeared in November 2013.

Figure 3 A muddy silty water outlet at bank of Kali River (Technical research report, 2014)

Sinkholes formed from November 2013 to June 2014

During the June 2014 survey, the trace of a number of sinkholes previously formed in November 2013 could be typically observed in both sides of the Duhuni Khola (green dots in Figure 4 and observation points 1 to 30 in Figure 5). All the sinkholes were completely filled, except for the sinkhole at point 6 (Figure 5). Originally, it had a diameter of about 10m and depth of about 7m. But, at the time of the survey, the upper part was already filled by sediments, and the measured depth was less than 4m.

According to local residence the first sinkhole appeared in November 2013 at point 3 (Figure 5). Since then, more than 150 sinkholes developed in this area. A typical circular-shape sinkhole appeared in Nov. 2013 is shown in Figure 6(a) (mysansar.com).

Figure 6(b) shows a small sinkhole appeared at point 2 (Figure 5), just one day before the survey team visited this area in June 2014. Note that, although the sinkhole in Figure 6(b) has a small diameter at the surface, its diameter is much larger in the subsurface (red dotted line). Such spherical shape is due to the fact that the soil in the upper part of the sinkhole was retained by the root system of the grass binding the surface soil.

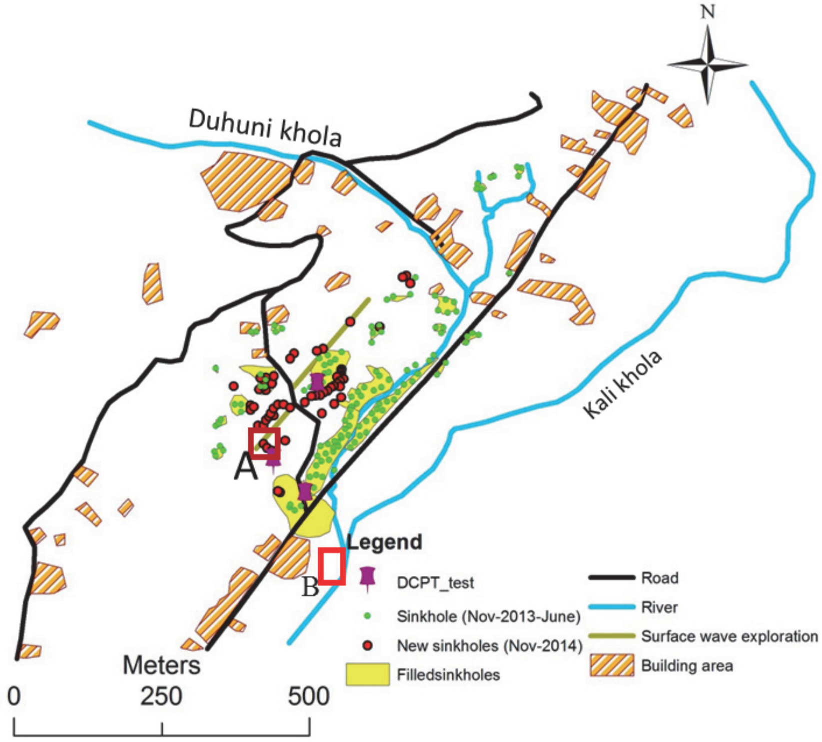

Figure 4　Detailed map of the sinkhole damaged area in Armala

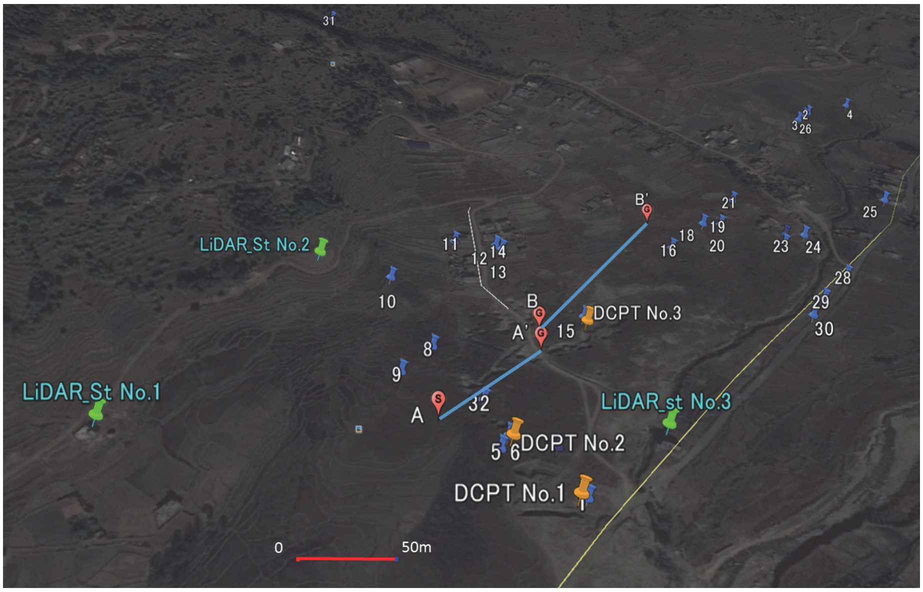

Figure 5　Survey map of the Armala area

The sinkholes affected not only the agricultural farmland. It also caused the collapse of cowshed Figure 7(a) at point 11 (Figure 5), and kitchen of the local residents Figure 7(b) at point 25 (Figure 5). Homeowner said that about 60 m^3 of filling material were used to fill the sinkhole shown in Figure 7 (a).

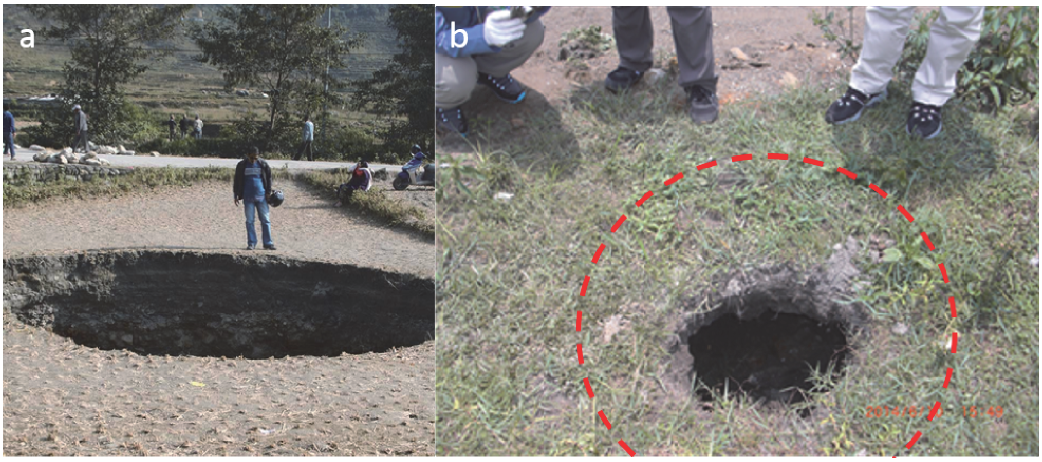

Figure 6 (a) a typical sinkhole formed on Nov. 2013 (source: mysansar.com); and (b) a sinkhole formed in June 2014

Figure 7 Typical effects of sinkhole on residential properties: (a) collapsed cowshed and (b) collapsed kitchen

Immediately after the occurrence of sinkholes, a wide area affected by the cave-in was backfilled (Figure 8) by using gravelly soil retrieved from nearby quarries, which is identified by a yellow color filled area in Figure 5. At the time of the first damage survey in June 2014, most of those sinkholes gave the impression to be essentially fully backfilled Figure 8. However, photos taken in November 2014 clearly show that the backfilling was not an adequate solution as most of former sinkholes re-activated Figure 9 likely in August 2014 during the peak rainy season in Pokhara valley.

Sinkholes formed between August 2014 and November 2014

During the November 2014 survey, a number of sinkholes of recent formation (understood to be developed in August 2014) were mostly observed in the west side of the field survey area. In the map shown in Figure 5, it can be seen that the new sinkholes (red dots) are concentrated on the western side of the old sinkholes. Some of the new sinkholes may be old sinkholes reactivated during the rainy season.

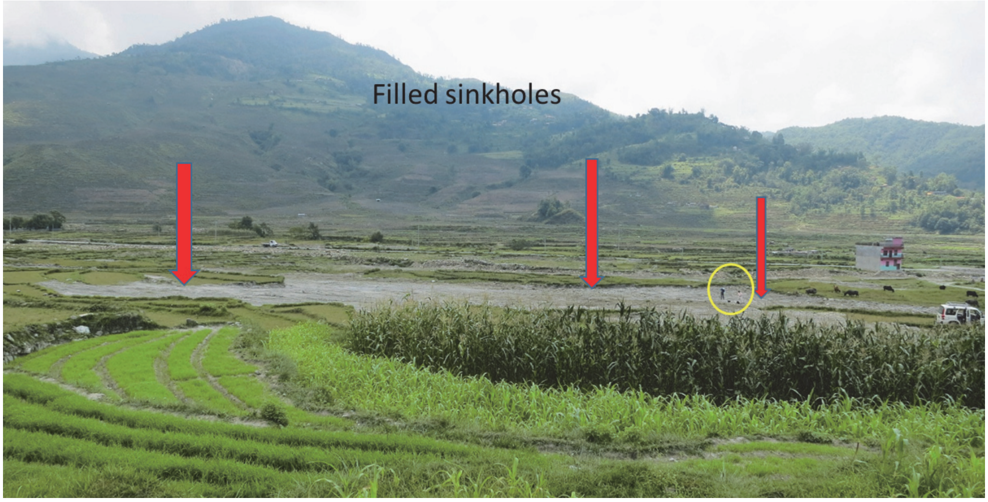

Figure 8 Photo of the sinkholes backfilled area taken in June 2014 (red arrows show backfilled area; yellow circle indicates the location of Dynamic Cone Penetration Test No.3)

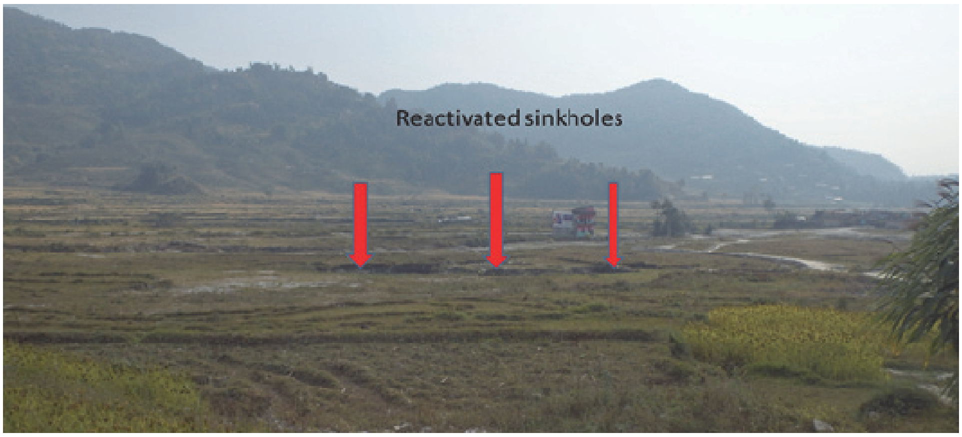

Figure 9 Re-activated sinkholes area observed in November 2014 (c.f. Figure 8)

Among many, sinkholes N1, N2 and N3 in the area A in Figure 5 were found of particular interests. They were developed in a delimited area of approximately 10×20 m, as shown in the schematic map reported in Figure 10. They have a circular pattern and a diameter ranging from 4.6 m (N3) up to 6.8 m (N1). Their depth measured at the top of collapsed soil varied from 2.2 m (N1, N3) to a maximum of 3.5 m (N2). According to local residents, N1 was the first sinkhole to be formed. Few days later, N2 was caved-in and finally N3 was developed.

This progressive formation of several sinkholes along a straight line (moving along upstream 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 N1 until a new cave-in (N2) was formed. In similar way, N3 was later developed. According to local residents, same pattern of the sinkholes also appeared in November 2013.

This process is also seen in other areas. Most of the newly developed sinkholes are located in the upstream side of the underground water flow. As an immediate mitigation works, all the old sinkholes were filled by the local government. This practice could disrupt the underground water flow so that ultimately more caving process started producing reactivation of sinkholes.

Figure 10 Series of sinkholes appeared in the area A reported in Figure 5

Note that due to loose conditions of backfilled material, it is expected that the development of a reactivated sinkhole is much quicker than that of an original sinkhole where natural compacted soils was gradually eroded by water.

Possible mechanisms of sinkhole in Armala area

The groundwater flow is the triggering factor involved in the generation of sinkhole observed in this study. In fact, it is assumed that in Armala area, there has been in act an erosion process (probably lasting hundreds of years), where water gradually dissolved small parts of soluble soil, creating cavities beneath ground surface (Figure 11(a)). However, such cavities were stable and likely small in size. In fact, despite the high sinkhole risk, the concrete formation of sinkhole was rarely observed in past decades in Armala area.

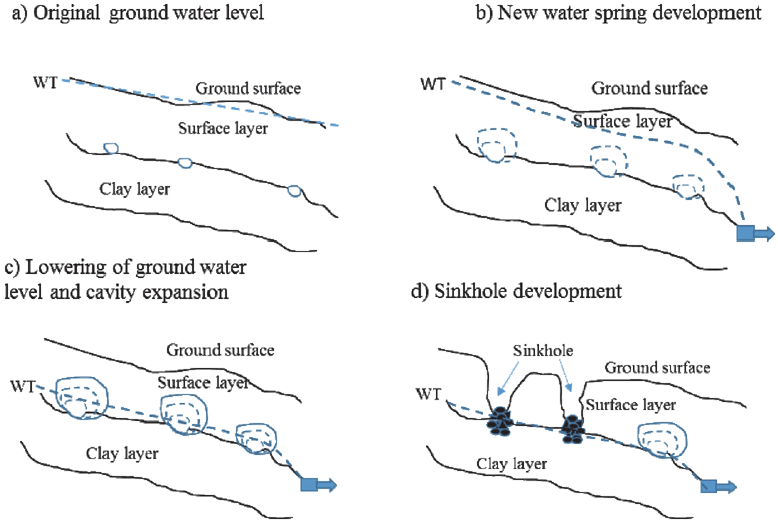

Figure 11 Probable mechanisms of sinkhole observed in Armala area

Nevertheless, in November 2013, suddenly, a water spring was observed for the first time by local resident (Figure 3). It was rapidly followed by formation of a number of sinkholes as already described earlier. Authors believed that the formation of water spring induced a change in the groundwater level, i.e. water table decline (Figure 11 (b)).

The drastic fall in groundwater level and its fluctuation during rainy season, accelerated the erosion process (as evidenced by mud water observed at the water spring outlet) and cavities enlargement (Figure 11 (c)). 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 become instable and collapsed (Figure 11(d)).

FIELD INVESTIGATION

A major challenges faced in this sinkhole damage site investigation was the identification and delineation of underground cavities. These structures are usually unpredictable and their effects can either lead to a slow and gradual subsidence or to a catastrophic sudden collapse (Zhou and Beak, 2011). Usually, geological and geomorphological methods are used to map geological formations for probable sinkhole. Yet, they are not adequate for the detection and precise location of cavities. The problem becomes more complex in such area where the presence of natural cavities is not known. Alternatively, to identify the location of cavities in the subsurface as well as the presence subsurface channels a geophysical method can be used.

Therefore, in this survey dynamic cone penetration tests (DCPTs) and surface wave exploration methods were used to identify the thickness of the cavity bearing formation and their location. Light Detection and Ranging (LiDAR) survey was also carried out in the study area to obtain the 3-D image of the study area.

Dynamic Cone Penetration Test (DCPT)

DCPTs were carried out in three different location of damaged area (Figures 4 and 5) in June 2014. The objective of these tests was to find out the thickness of the cavity bearing formation and bearing capacity of the layers. The first DCPT was carried out at the bottom of non-filled sinkhole, the second

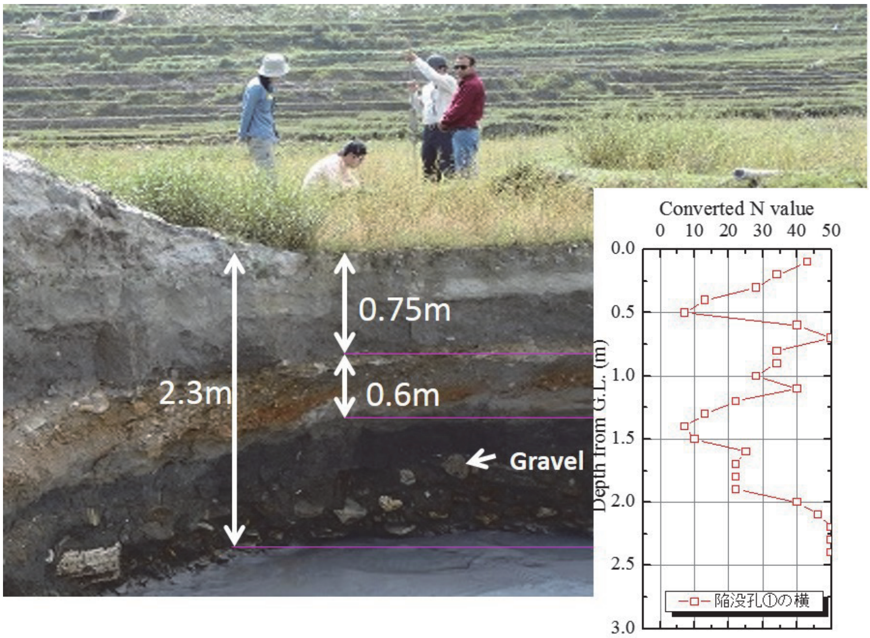

Figure 12 Soil profile and DCPT result in the location 2 observed in Sinkhole on June 2014

one was carried out just adjacent to the sinkhole as shown in Figure 12, and the third test was carried out at top of the filled material shown in Figure 8. Results of DCPTs were correlated with stratigraphy and structure study of the deposits (Figure 12).

As already mentioned earlier, this area is composed of recent flood plain deposits. There is a thick gravel layer at shallow depth. Thus, all the DCPTs at all the points could not penetrate more than 7 m depth. The first location, penetration depth was up to 6.5 m. The remaining two were 2.5 m and 3.9 m, respectively.

In the case of DCPT No. 2, the converted DCPT-N values are plotted in Figure 12. The upper layers of surface soil could be penetrated until reaching the gravel layer, where even by hitting more than 150 times the penetration process stopped.

From the third DCPT, it is concluded that the used filling material is also gravelly soil. However, the compaction at the surface is not good enough because the N-value measure is very low.

From these test results, it is assumed that likely the cave-in started just below the gravelly layer. Then progressively the cavity size increased and finally the loose upper layer collapsed.

Surface wave exploration

This is a non-destructive geophysical method to investigate subsurface structures. In this method the near surface problems are studied by using dispersive character of Rayleigh waves.

The surveys were performed along two different patterns (two green lines) in Figure 4 and A-A' and B-B' in Figure 5 using surface wave exploration. The total length of survey is over 250 m. The testing conditions consist of: 24 vertical-component geo-phones deployed with 1 m interval; and a 5 kg hammer used as a source of surface waves. Source was also moved with 1 m interval. The nearest source to receiver offset was 0.5 m. An OYO MCSEIS-SW was used for data acquisition. Figure 13 shows typical surface wave exploration alignment used in this investigation.

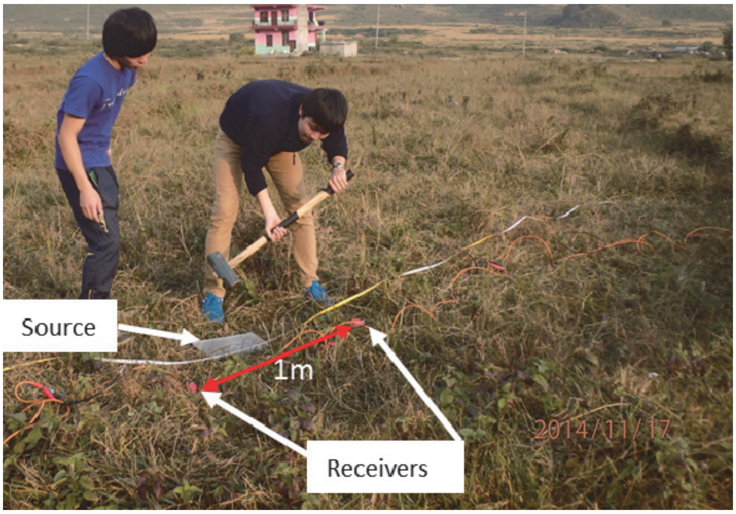

Figure 13 Surface wave exploration method used in this invetigation

Typical results of surface wave exploration for a section of 25 mm are shown in Figure 14. One can see that the shear wave velocity for the surface layer is in the range of 150-180 m/s, confirming the presence of a very loose sand layer of thickness 1.5 m. The underneath gravel has a higher velocity, than surface layer, of about 240 m/s. Moreover, the stiff soil below 4 m depth has a shear wave velocity greater than 350 m/s. It should be noted that, the results obtained for a depth from ground surface below 15 m were considered not reliable because technical limitation of the surface wave measurement method used.

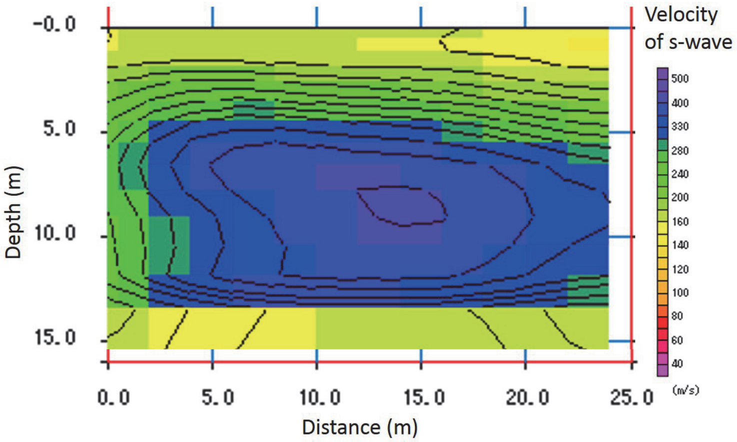

Figure 14 A typical profile of surface wave exploration

LiDAR survey

In November 2014, to acquire the entire 3-D image of the sinkhole damage area, a survey was conducted by using the Light Detection And Ranging (LiDAR) shown in Figure 15. The area was scanned from three locations as shown in Figure 5. The individual 3D digital surface models were then combined to create the entire terrain model of the study area. Figure 16 shows a bird-eye view of the sinkhole affected area. The black part at the lower right corner of the image is the hidden part behind the cliffs. The black spots highlighted by yellow circle are recent and reactivated sinkholes.

Figure 15 A LiDAR machine LPM-321, used for scanning survey area

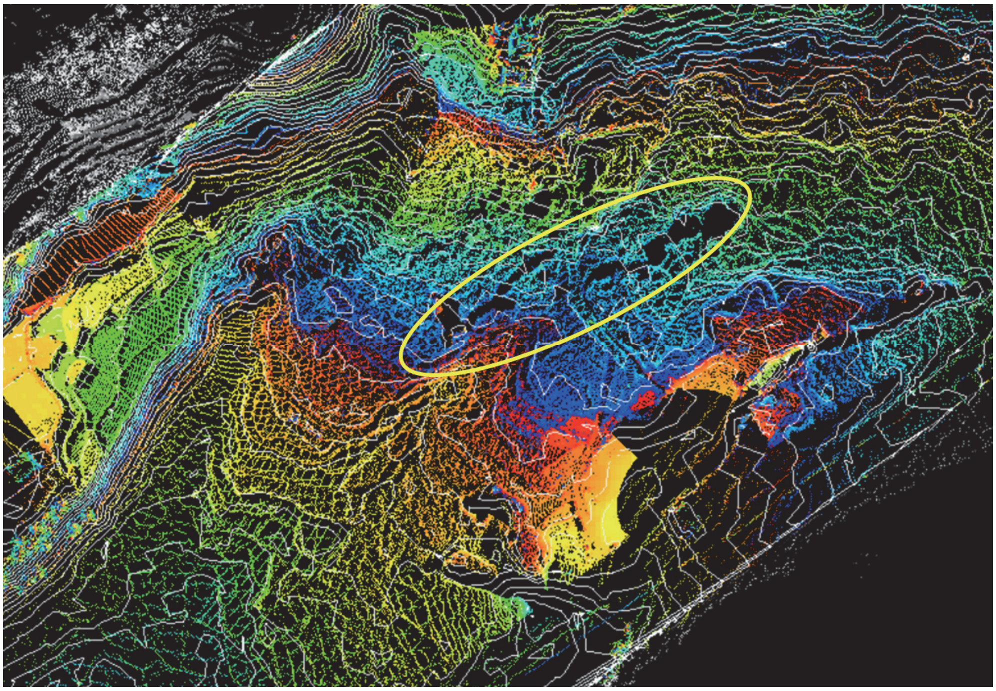

Figure 16 Birds eye view of the sinkhole effected area

MITIGATION MEASURES AIMED AT REDUCING SINKHOLE RISK

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 (Gutierrez et al., 2008).

As explained before, as a possible countermeasure, the government agency backfilled a number of sinkhole. However, it was clearly a temporary and not satisfactory solution since the majority of the sinkholes re-activated during the rainy season.

At the time of the first visit in Armala, Authors strongly suggested to the local resident to review the land use planning and regulation of the area particularly inhibit irrigation in this area, evacuate building located very close to damaged sinkhole zone. Also, local government agency was advised to inhibit any new construction in the area.

After the second visit to the site investigation, Authors did some geophysical survey to identify the cause and mechanisms of sinkhole observed in Armala area. On this basis, suitable engineering countermeasures aimed at diminishing sinkhole risk are now being considered, such as:

- Preventing water withdrawal and controlling irrigation;
- Prevent the fluctuation of water table;
- Using effective drainage system and diverting surface runoff.

Improving the ground by compaction or ground injection to increase the strength and baring capacity of the soils.

SUMMARY

Since November 2013, the unpredicted formation of a significant number of sinkholes has been observed in Armala area, Pokhara Valley (Nepal). Considering that Nepal is a seismic prone country, there is a very high potential that an upcoming strong earthquake may produce catastrophic effects in the Armala area. In fact, it could cause the development of a significant number of large sinkholes posing enormous risk to people residing in Armala area. In order to mitigate the effects of such combined geo-risks, new insights into such sinkhole formation and their features is crucial. The Authors conducted sinkhole damage survey in 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 the triggering factor involved in the generation of the sinkhole observed in this study.
2. Sinkholes caused severe damage to residential property, roads, crops land etc. However, there are still many hidden cavities that likely will generate new a sinkhole, since the erosion process is still in act.
3. As a possible countermeasure, the government agency backfilled a number of sinkhole. However, it was clearly a temporary and not adequate solution since the majority of the sinkholes re-activated during the rainy season.
4. The result of the DCPTs and surface wave exploration shows there is a loose layer laying on the 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.

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