Investigation into the multiple recent sinkholes in Pokhara, Nepal

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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 countermeasures for reducing sinkhole risk, detailed investigations into the cause and the formation mechanism of the sinkholes are crucial. Preliminary surveys were conducted in June 2014 and November 2014. 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 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 preliminary field investigation, possible sinkhole formation mechanisms are considered. A risk of sinkhole does not seem to disappear as white turbid water continuously springs. It indicates that the internal erosion of white clayey silt layer is still in progress. In August 2015, a boring was carried out beside one of the largest sinkholes. The overall structure of ground layers was first revealed and a 2.5m high cavity at 7.5-10m deep from the ground surface was found within a thick white clayey silt layer. Further ground investigations including surface wave exploration were conducted in December 2015 and the results are reported.

1 INTRODUCTION

A number of sinkholes occurred in Pokhara, Nepal, in November 2013. The locations of sinkholes are mostly on fields of rice and other crops. About 50 families had to evacuate since sinkholes also appeared beside houses. They said that more than 200 sinkholes appeared and eventually many of them were connected each other. Estimated total volume of the sinkholes was about 10000 m^3.

The field investigations were carried out in 2014 and 2015 to clarify the mechanism of sinkhole formation and possible countermeasures. At each investigation, the new sinkholes have been observed, indicating that the primary process of sinkhole formation is still continued. The results obtained from investigation in 2014 were reported in Pokhrel et al. (2015). This paper provides the major outcomes from the investigation carried out in 2015.

2 OUTLINE OF SINKHOLE AREA

2.1 *Location*

Location of the multiple sinkholes is North-Eastern part of Pokhara Valley, in the central Nepal, where they have heavy rainfall usually from June to August. The average monthly precipitation in July reaches 900 mm.

Figure 1 shows the aerial photo of the sinkhole area. There is a big river called Kali Khola running through the area. A relatively small river, named Duhuli Khola, flows into Kali Khola. Many sinkholes occurred along Duhuli Khola as indicated in Figure 1.

2.2 *Geology and topography*

Calcareous clayey silt layer spread around this area. Experts have already pointed out a risk of sinkholes. Building construction is not recommended in the area since the ground is very soft, consisting of soft clay, peat, or calcareous soil. Topographically, the study area is a low-elevated zone. There is a gentle slope in the south-east direction, while a steep slope can be seen in the north-west parts. Considering that Pokhara Valley is a most heavy-rainfall area in Nepal, large amount of water seems to gather from surroundings and infiltrate in this area.

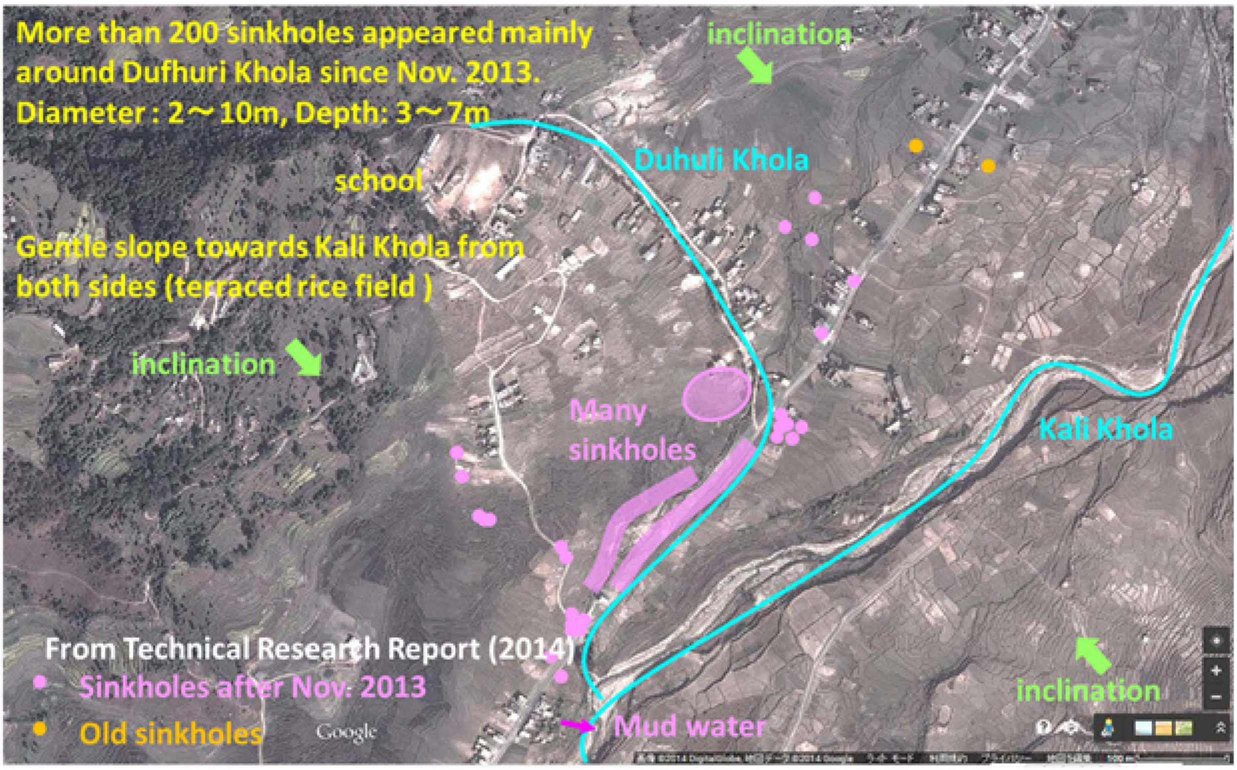

Figure 1. Outline of the sinkhole area

2.3 *Onset of Sinkholes in November 2013*

According to local residents, a muddy silty water outlet was observed at the Kali Khola riverbank (as indicated in figure 1) about a week before the first sinkhole appeared in November 2013 (Technical report, 2014). Since then, more than 150 sinkholes developed in this area until June 2014 and more than 200 sinkholes were reported up to November 2014. Typical sinkholes are 2 to 10 m in diameter and 2 to 7 m in depth, having circular opening in the ground surface. Most of the sinkholes seemed to be backfilled in 2013.

Although the first sinkhole appeared in the northern part of the site investigation, the majority of the sinkholes actually were formed along the Duhuni Khola between 25 November and 5 December 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.

3 FIELD INVESTIGATION

3.1 *Reactivation of sinkholes*

Field investigations were carried out in June and November in 2014, and July, August and December in 2015. In June 2014, we found that all the sinkholes had been completely backfilled except for two. At the bottom of these unfilled sinkholes, soft white clayey silt sediment was found as shown in Figure 2. The white deposit seemed to be brought by water springing at the bottom or the side of the sinkhole as shown in Figure 3. Sprung water was white turbid, indicating that the subsurface internal erosion continued.

In November 2014, we observed a lot of sinkholes, including newly formed ones and reactivation of sinkholes for backfilled ones. Figure 4 compares photos of the same location taken in June and November 2014. The process of sinkhole formation seems to be still continuing. Especially after the rainy season, many new or reactivated sinkholes appear. Figure 5 presents an aerial photo of south west parts of the area taken in December 2015. Most of the sinkholes observed in Figure 5 are reactivated ones and they are in lines, implying that the subsurface water pathway may be developed and cause the internal erosion.

Figure 2. White silty clay deposit

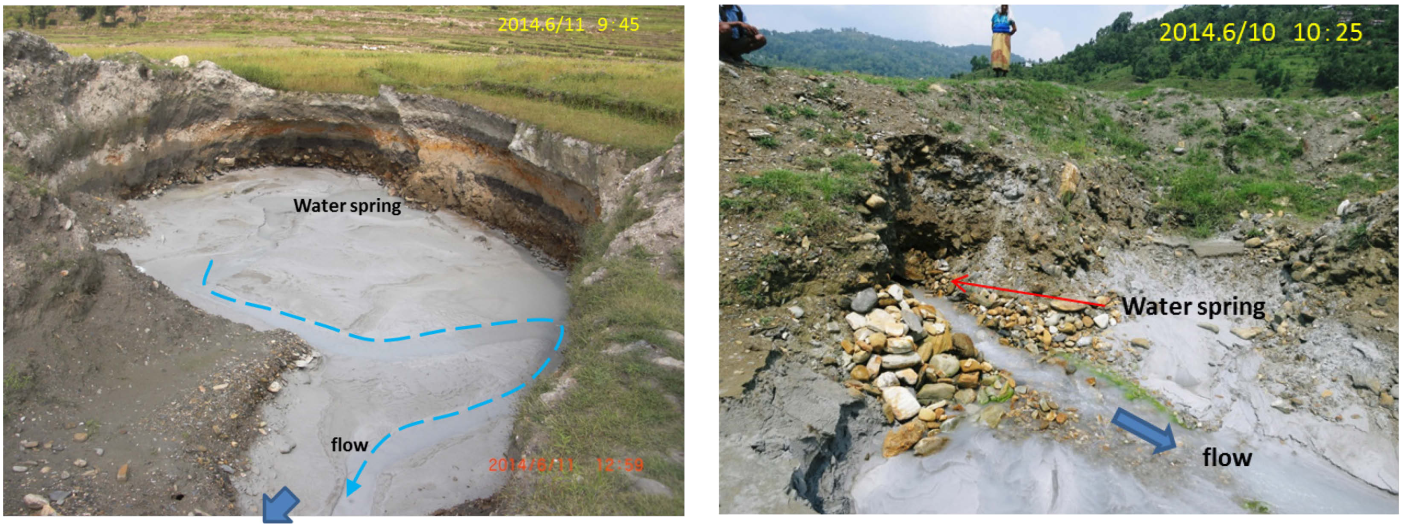

Figure 3. White turbid water spring at the sinkholes

Filled sinkhole (June 2014) Sinkhole appeared again (Nov. 2014)

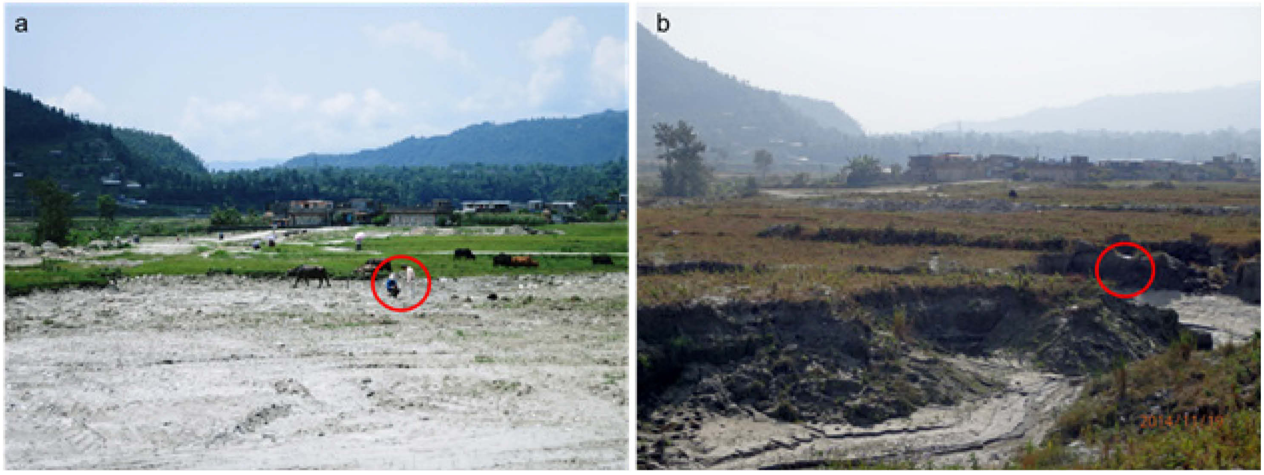

Figure 4. re-occurrence of backfilled sinkholes

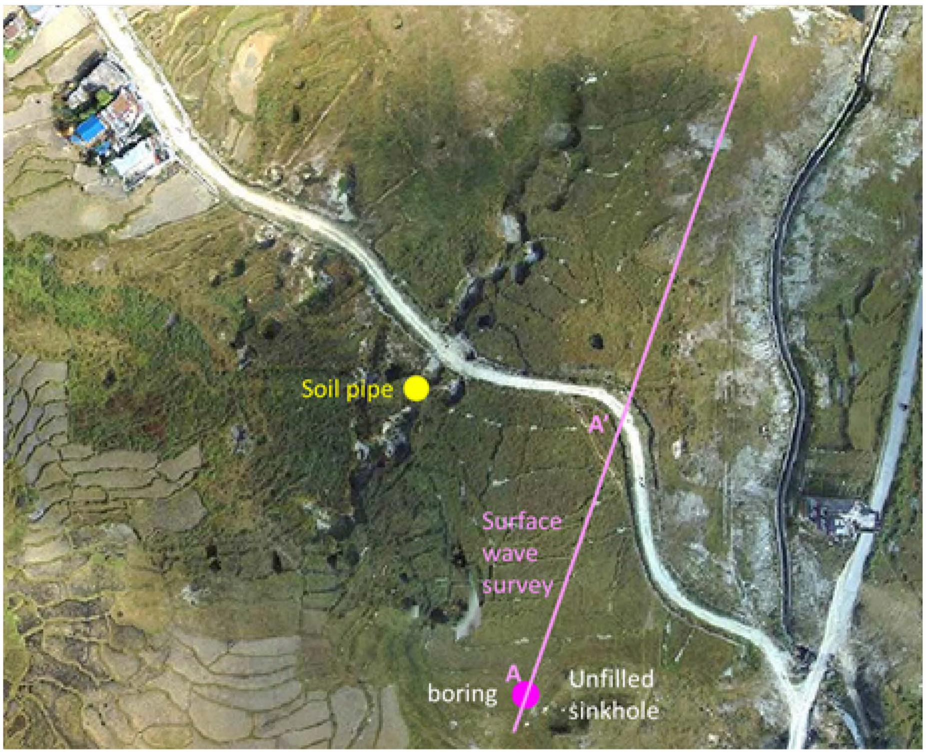

Figure 5. Aerial photo of the area taken in December 2015

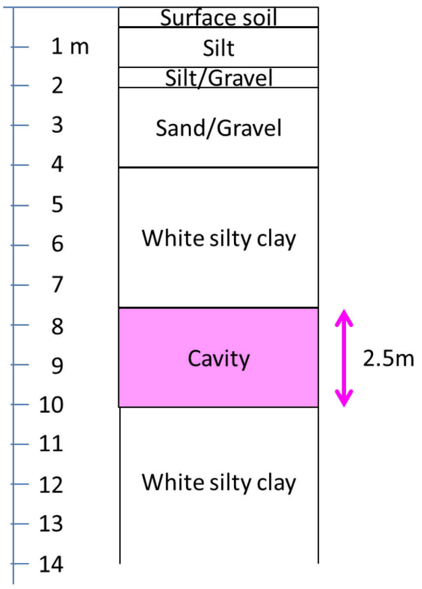

Figure 6. a subsurface cavity identified from borehole survey

3.2 *Boring survey*

Boring survey was conducted in August 2015, beside one of the unfilled sinkhole, indicated in Figure 5. As shown in Figure 6, a thick white silty clay layer was found below GL-4m and a cavity of 2.5m high was discovered at GL-7.5 to 10m. The white silty clay seems to be very stiff. The SPT values of the layer were over 50.

3.3 *Surface wave test*

Surface wave exploration is a non-destructive geophysical method widely used to investigate subsurface structures. 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.

Surface wave surveys were performed along four lines in the area. The testing conditions consist of 24 vertical-component geo-phones 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.

A part of the results of surface wave test along the line A are shown in Figure 7. The line A is passing on the borehole as indicated in Figure 5. Figure 7 presents S wave velocity profile for line A-A’. Although it was confirmed that the 2.5m high subsurface cavity exist at the borehole point, it was not clearly identified in the profile of S wave velocities obtained from surface wave survey. A low velocity section observed at -40 m and 40-50 m from the borehole point may indicate potential cavities or loosening in the ground.

3.4 *Soil pipe*

The sign of subsurface water pathway was found in the bottom of one of sinkholes, as shown in Figure 8. The soil pipe developed in a white silty clay layer at GL-6.0m. White turbid water stayed around the pipe. A lot of reactivated sinkholes existed at the location of soil pipe as shown in Figure 5.

4 POSSIBLE MECHANISMS OF SINKHOLES

The groundwater flow is the triggering factor involved in the generation of sinkholes. In fact, it is assumed that in this area, there has been an active erosion process, where water gradually dissolved soluble soil, creating cavities beneath the ground surface. Pokhrel et al. (2015) assumed that the erosion process occurred at the boundary between surface layer and white silty clay due to the change of underwater condition, as demonstrated in Figure 9. In the investigation in 2015, the results almost support the hypothesis proposed by them but it was confirmed that the erosion took place within the white silty clay layer, not at the boundary.

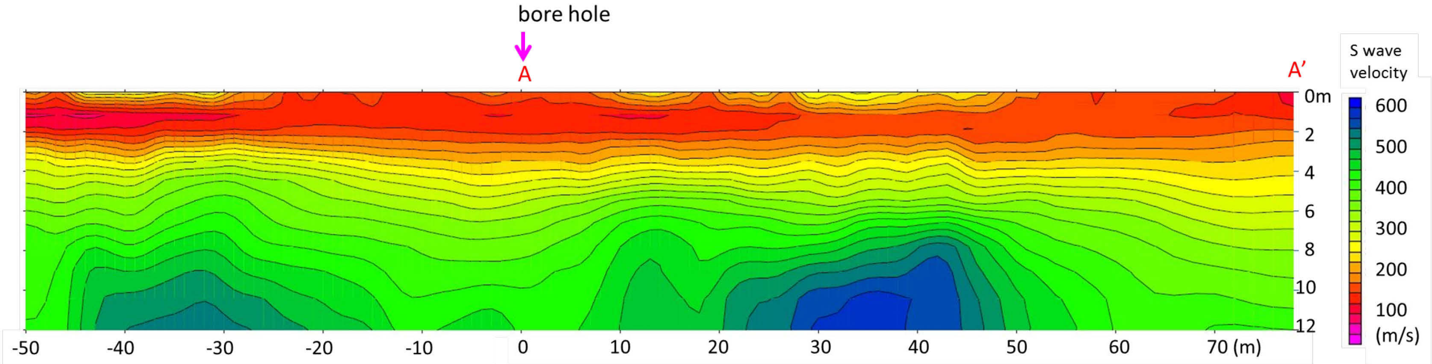

Figure 7. S wave velocity profile obtained from the surface wave survey for line A-A’

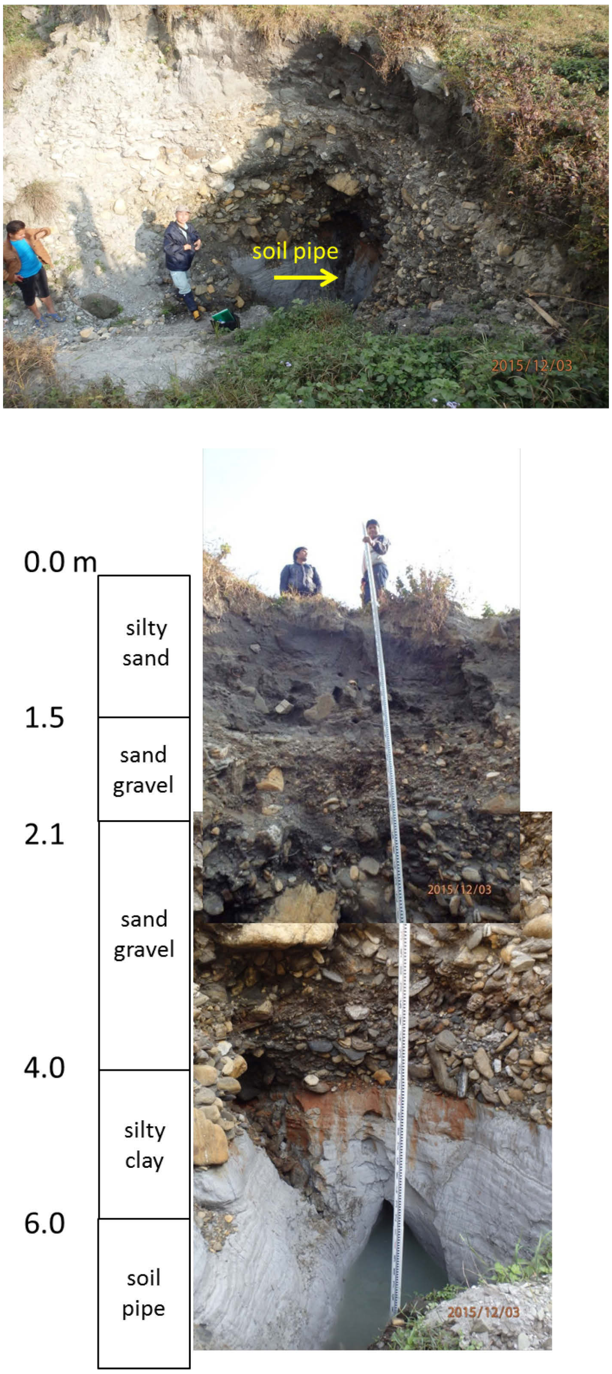

Figure 8. Soil pipe found at one of sinkholes

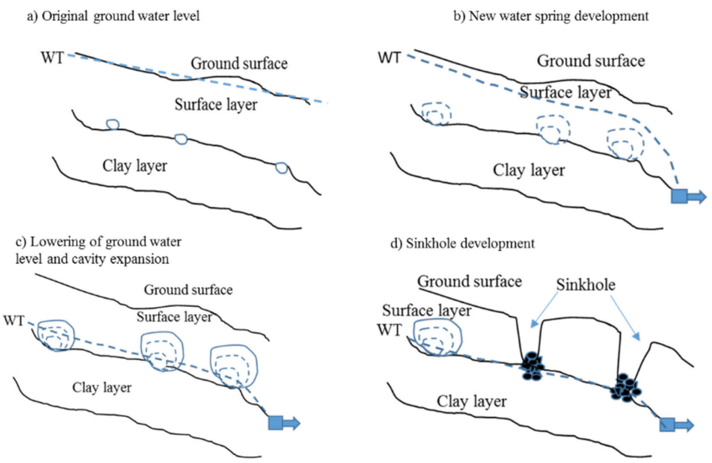

Figure 9. Mechanism of subsurface development (Pokhrel et al. 2015)

5 CONCLUSIONS

Since November 2013, a significant number of sinkholes have been observed in the Armala area, Pokhara Valley, in Nepal, posing enormous risk to people residing in the affected area. The authors conducted field investigations in the area to study the formation of such sinkholes and identify the location of hidden cavities that could develop new sinkholes. The results from the survey conducted in 2015 can be summarized as follows:

1. The formation of sinkholes has not been diminished so far. Especially after the rainy season, in the investigation in post monsoon season, a number of new or reactivated sinkholes are observed. It implies that the internal erosion process is still continuing.
2. Sinkholes are often in a line, concentrated or connected, indicating the presence of underground water paths connecting sinkholes.
3. Subsurface water pathways exist in a layer of white silty clay. The layer is relatively stiff and clear form of soil pipe was found.
4. Such underground cavities were not clearly identified in the surface wave survey.

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