A Forensic Investigation on Sinkhole Formation in Urban Area

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ABSTRACT

The formation of sinkholes in urban areas in different geologic topographies results in sudden ground collapse. People, properties and/or moving vehicles fall into these sinkholes without any warning. The sinkhole is often developed from an enlarging underground cavity progressively and unnoticeably until the occurrence of sudden ground collapse. The sudden ground collapse can cause personal injuries and loss of properties. Although the sinkhole or ground collapse occurs suddenly without any warning, the underground cavity may develop suddenly or through a prolonged period depending on the underground cavity formation mechanism. The forensic investigation on the formation of a sinkhole in the urban area of Hong Kong is presented in this paper.

INTRODUCTION

The sudden occurrences of sinkholes or ground collapse in urban areas, such as Hong Kong, can be disastrous (Friend 2002). The sinkhole can be dry or submerged in water. People, properties, and/or moving vehicles can fall into sinkholes suddenly without any warning as shown in Figures 1 & 2, resulting in personal injuries and/or property damage.

Most sinkholes are developed from existing underground cavities. Although the sinkhole occurs suddenly, the underground cavity can be developed suddenly or through a prolonged period depending on the formation mechanism. Underground cavities and the subsequent sinkhole can be developed rapidly by bursting of water-carrying utilities. Such formation mechanism is obvious and a forensic investigation is thus not necessary.

However, the cause for sinkhole formation initiated by an underground cavities developed through a prolonged period requires a forensic investigation to allocate the responsibility of the incident and to prevent the formation of such underground cavity in urban area in the future, thus preventing the occurrence of sinkhole and personal and property damage. The forensic investigation of a real-life case in Hong Kong is presented in this paper.

Figure 1. Falling of people into a sinkhole.

Figure 2. Falling of a drinking water delivery truck into a sinkhole.

POSSIBLE MECHANISMS OF SINKHOLE FORMATION

Formation of sinkhole occurs in stages. However, the duration of each stage may vary depending on the formation mechanism. These different stages are outlined as follows:

Sinkhole or Sudden Ground Collapse. A sinkhole or ground collapse occurs suddenly without any warning. The ground surface suddenly cracks and the surface materials collapse into an underground cavity, resulting in the formation of an opening on the ground surface. The sinkhole may be dry or submerged in water. In most cases, the sudden ground collapse is triggered by the application of additional load on the ground surface, such as the weight of a pedestrian walking by or that of a vehicle driving by, resulting in the falling of the pedestrian or vehicle into the sinkhole as shown in Figures 1 & 2.

Sinkholes can also occur when the load imposed on the ground surface is substantially increased. For example, the substantial weights of industrial or runoff-storage ponds constructed on ground surface can trigger an underground collapse of supporting materials, thus forming a sinkhole. However, such sinkhole formation mechanism is beyond the scope of this paper.

Formation of Soil Arch. The formation of a sinkhole is often initiated by the existence of an underground cavity. As the underground cavity is being developed, the ground surface is supported by the arching effect of the soil spanning across the underground cavity. Terzaghi discovered the existence of arching effect in soil and described the soil arching process as the transfer of pressure from a yielding mass of soil onto adjacent stationary parts (Terzaghi *et al*. 1996). Two conditions are considered essential for the generation of the soil arching effect depending on the assumed soil arching pressure distribution: (1) an uneven or relative displacement of soil mass; and (2) the existence of arch springing (Handy 1985; Harrop-Williams 1989).

Nonetheless, the practical effect of soil arching is that the load imposed on the ground surface above an underground void is temporarily supported by the soil arch. As the underground cavity is being enlarged by erosion progressively, the span of the soil arch is increased gradually and the load-carrying capacity of the soil arch is diminishing accordingly. When the load imposed on the ground surface eventually exceeds the load-carrying capacity of the soil arch, the soil arch fails suddenly and the surface materials collapse into the underground cavity, resulting in the formation of the sinkhole.

Formation of Underground Cavity. A sinkhole is often initiated by the development of an underground cavity. However, there are different possible mechanisms for the formation of the underground cavity.

It may involve natural processes of erosion or gradual removal of slightly soluble bedrock (such as limestone) by percolating water, the collapse of a cave roof, or a lowering of the groundwater table. Underground cavities in karst topography can also develop through the process of suffosion which occurs when loose cohesionless materials are overlying a limestone substratum containing fissures and joints. Rain and surface water gradually wash these materials through the fissures into caves beneath. The process creates a depression on the landscape of varying depth. Moreover, groundwater may dissolve the carbonate cementing sandstone particles together and then carry the loosen particles away, gradually forming an underground cavity.

Underground cavities can also develop from abandoned mines and salt cavern storage in salt domes in places such as Louisiana, Mississippi and Texas of the United States by intentional human activities.

Underground cavities can also develop when natural water-drainage patterns are changed and new water-diversion systems are developed. The changes can be caused by temporary dewatering for the construction of underground structures, such as basements and foundations. However, more commonly, underground cavities occur in urban areas as a result of soil erosion caused by water main bursts or sewer collapses when old pipes deteriorate with time. They can also occur from the over-pumping and extraction of groundwater and subsurface fluids.

Because of the many possible mechanisms for underground cavity formation, forensic studies are often required to identify the mechanism for the particular case and to allocate the responsibility of the damage so caused.

THE INCIDENT

The ground surface adjacent to a construction site fell into an underground cavity forming a sinkhole abruptly. A pedestrian fell to the bottom of the sinkhole and suffered multiple injuries. The sinkhole of approximately 3.5 m long, 2.5 m wide and 3.7 deep with the formation of an opening of approximately 1 m by 1 m formed at the paving blocks of the pedestrian pavement.

The construction site in question was located in the downtown area of Hong Kong where foundation and excavation & lateral support works were being constructed for a hotel development project during the occurrence of the sinkhole. The foundation works included large-diameter bored piles. The excavation and lateral support works included a cofferdam enclosing the four sides of the site made of pipe piles and grout curtain and the associated strutting system constructed to facilitate the excavation for the construction of pile cap and basement. The forensic investigation was conducted to determine whether or not the sinkhole was caused by the construction activities at the site.

THE FORENSIC INVESTIGATION

Available Information. Available information of the project including: (1) borehole logs obtained from the ground investigation program specifically designed for the project; (2) geotechnical engineering design parameters and design assumptions adopted for the analyses and design of the project; (3) design calculations; (4) design drawings of the foundation and excavation and lateral support; (5) results of the pumping test after completion of the cofferdam; (6) site monitoring records of groundwater levels, settlements of adjacent ground, settlement of nearby utilities, tilting of adjacent buildings, and ground vibration during construction; (7) construction and maintenance records of nearby water-carrying utilities; (8) records of routine inspections by government officials; (9) statements of eye witnesses of the incident; etc.; were scrutinized for its validity. More importantly, the information was used to conduct the forensic study for the incident.

Field Investigation. A specifically designed field investigation program was conducted for the forensic study. The field investigation program included: (1) observations made during backfilling of the sinkhole; (2) field inspection of the cofferdam; (3) surveying of existing water-carrying utilities and detection of potential subsurface cavities around the site; and (4) GCO probe tests, and Standard Penetration Tests (SPTs) and soil sampling at locations around the site.

The GCO Probe is a dynamic probing tool comprises of a sectional rod with a cone of 25 mm in diameter fitted at the end. The diameter of the base of the cone is 12 mm larger than that of the rod. It is driven into the ground by a 10-kg mass falling through a distance of 300 mm. Probe results are normally reported as number of blows per 100 mm penetration. They are very useful for assessing the depth and degree of compaction of buried fill, making comparative qualitative assessments of ground characteristics, and supplementing the information obtained from trial pits and boreholes (Geotechnical Engineering Office 1987). In particular, the GCO Probe test may be a very effective way to locate any underground cavities around the site.

FORENSIC ANALYSES

Assumption. The sinkhole was not formed by the process of dissolution or suffosion as it was not located in karst topography. The underground cavity causing the formation of the sinkhole was thus not developed by natural processes but by artificial activities that might include construction activities at the site.

Hypothesis. The sinkhole was initiated by an existing underground cavity. The underground cavity was formed by removal of subsurface soil. Therefore, the soil particles must have migrated somewhere. The subject of investigation is to investigate whether or not the removal of subsurface soil was caused by construction activities at the site.

Review of the Statements of Eye Witnesses. The statements of eye witnesses were carefully reviewed, in particular, the statement of the victim who fell into the sinkhole. He did not notice anything abnormal near the sinkhole on the pedestrian pavement, in particular, he did not notice any bumps or depressions prior to his fall. His observations were supported by the site monitoring data collected prior to the incident. He fell almost 4 m to the bottom of the sinkhole and he sank only to his ankles, indicating the layer of loose soil was very thin. He did not feel any stagnant or flowing water in the sinkhole.

It should be noted that he remained atop the paving blocks and the arching soil supporting the paving blocks prior to the incident. Therefore, he was supported on a mat of paving blocks mixing with soil originally located at the crown of the sinkhole when he reached the floor of the sinkhole. As a result, he felt that the soil was loose. It should be noted that the soil he touched was not the soil originally on the floor of the sinkhole. His observation cannot be relied on to locate the groundwater level in the sinkhole prior to the incident.

Observations made during backfilling of the sinkhole. The sinkhole was backfilled immediately by six trucks of concrete for public safety. The volume of concrete, approximately 42 m^3, used to backfill the sinkhole gave a good estimate of the actual volume of the sinkhole. It is very likely that the volume of concrete was slightly larger than the actual volume of the sinkhole as the loose soil in the sinkhole might have been compacted by the wet concrete. More importantly, the excavation was carefully observed during backfilling to observe whether or not any wet concrete might emerge into the excavation. No trace of concrete was found in the excavation, indicating the sinkhole was not directly connected to the excavation.

Review of the Cofferdam Design. The design of the cofferdam, in particular the seepage analyses, was carefully scrutinized for its adequacy. There were lateral earth pressures and water pressures acting on the cofferdam from outside and inside the excavation. As the ground level and groundwater level outside the cofferdam were higher than those inside the cofferdam, there was a net lateral earth pressure and a net water pressure acting on the cofferdam from the outside. The cofferdam was designed to withstand the net lateral earth pressures and the net water pressures acting on it for the structural stability of the excavation. Moreover, it was designed to control the seepage force induced by groundwater flow on the soil to prevent piping and heaving of the excavation floor for hydraulic stability of the excavation as shown in Figure 3. It was also designed to control the volumetric seepage flow rate into the excavation to acceptable levels as shown in Figure 4 so that it was possible to maintain dry working conditions in the excavation by pumping.

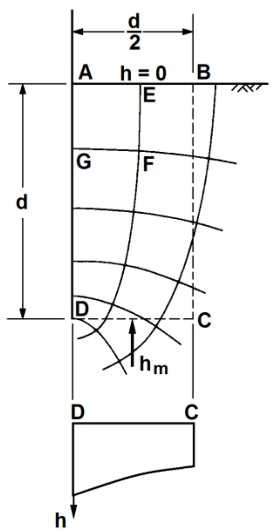

Figure 3. Analysis of heaving.

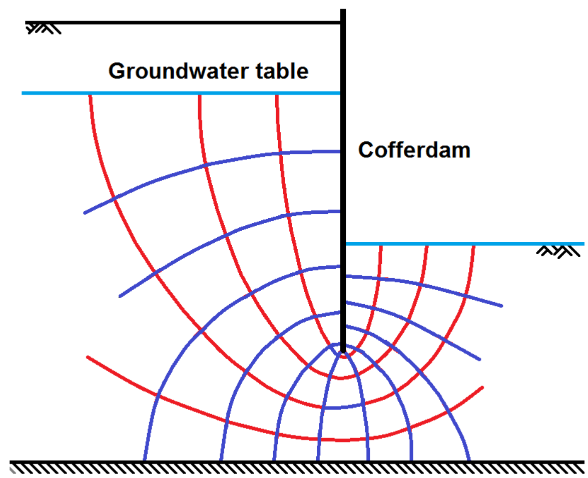

Figure 4. Analysis of groundwater seepage into excavation.

Basically, the inside and outside of the cofferdam was separated by a cofferdam built of pipe piles together with grout curtain and steel lagging plates. It was a steel box surrounding the excavation. Even if there were any cracks in the grout curtain, it was not probable that such a large amount of soil (a three-phase material containing air, water and solids) could pass through such a completely sealed structure and totally unnoticed by full-time resident site staff. The integrity of the grout curtain was substantiated by the results of the pumping test conducted upon completion of the cofferdam.

Review of Probing Test Results. The purposes of conducting the GCO Probe tests and SPTs around the Site were: (1) to identify and locate any existing cavities around the Site, if any; and (2) to reveal any concrete fragment so as to identify any connection between the sinkhole and the excavation. Many GCO probe tests could not penetrate to the toe level of pipe piles due to the presence of underground obstructions at shallow depths. As a result, SPTs were used to continue the investigation. No concrete fragment identifying any connection between the sinkhole and the excavation was found. The *in-situ* measurements of soil strength indicate the soil around the site has not been loosened by the construction works at the site.

Another underground cavity was discovered farther away from the site during the field investigation. If the underground cavity is allowed to grow unnoticed by erosion, it may eventually develop into a sinkhole similar to the sinkhole of the Incident, indicating the possibility of underground cavity formation without any involvement of construction activities at the site. It can be observed in Figure 5 that there are utilities and water in the underground cavity.

Review of Site Monitoring Data and Inspection Reports. All the site monitoring data, including ground settlements, utility settlements, building tilting, ground vibrations and groundwater levels, recorded from the commencement of the project did not exceed their respective alert levels stipulated in approved drawings. As revealed in the inspection reports submitted by government officers, there were no irregularities on the monitoring check points.

There was no observation in the site monitoring data on groundwater levels to justify any drawdown of groundwater table caused by the excavation and lateral support works at the site. However, the groundwater table may be drawn down locally in the underground cavity prior to the formation of the sinkhole as shown schematically in Figure 6 if the underground cavity was connected to somewhere thus providing a conduit for drainage of groundwater. The phenomenon explains why the victim did not feel any water in the sinkhole in addition to the fact that he was standing atop the paving blocks that fell with him into the sinkhole.

Figure 5. Utilities and water in the other underground cavity.

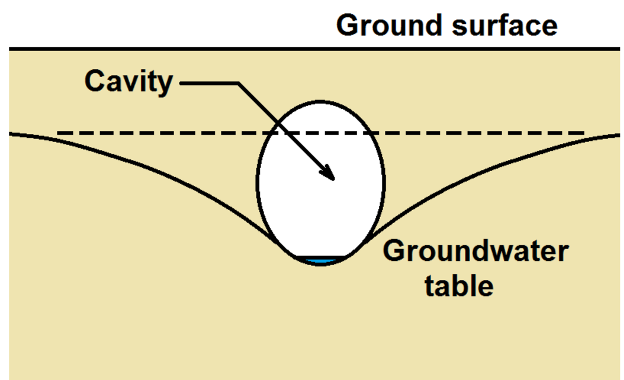

Figure 6. Local drawdown of groundwater in the underground cavity.

Review of Construction and Maintenance Records of Water-carrying Utilities. The results of the review reveal there were many water-carrying utilities near the sinkhole. Moreover, it was revealed in the maintenance records that these water-carrying utilities were leaking continuingly and maintenance was consistently required. It can be inferred that water is continuingly leaking into the subsurface and causing subsurface erosion.

Review of Utility Survey Results. The results of the utility survey indicate there are many leaking drains and manholes. Moreover, many manholes are blocked by soil, indicating soil particles are being migrated from the subsurface into these manholes through broken drains. The results are consistent with the maintenance records of water-carrying utilities.

Other Field Observations. Two sudden ground subsidence incidents occurred in the proximity of the site shortly before the occurrence of the sinkhole. When the two sinkholes were backfilled, no connections between the sinkholes and the excavation were identified. Moreover, government officers inspected the incidents did not attribute the causes of these incidents to the construction activities at the site.

Results of the Forensic Investigation. The results of the forensic investigation indicate the formation of the sinkhole in the urban area of Hong Kong is not related to the construction activities in a nearby site. The evidence also reveals that the formation of the underground cavity was probably caused by the leakage of water-carrying utilities. Therefore, it is necessary to develop reliable non-destructive methods to locate these underground cavities prior to the formation of sinkhole to protect public safety (Yeung and Ng 2009; Lam *et al*. 2011).

CONCLUSIONS

A forensic investigation was conducted on the sinkhole or sudden ground collapse occurred in the urban area of Hong Kong. Having scrutinized all the available information and conducted a specifically formulated field investigation program, it can be concluded that the formation of sinkhole in urban area of Hong Kong is probably caused by leakage of water-carrying utilities. Research on non-destructive technologies on the detection of underground cavities should be conducted to protect public safety.

REFERENCES

Friend, S. (2002). *Sinkholes*. Pineapple Press Inc., Sarasota, Florida.

Geotechnical Engineering Office (1987). *Guide to Site Investigation*. Geoguide 2, Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong SAR Government, Hong Kong.

Handy, R. (1985). "The arch in soil arching." *Journal of Geotechnical Engineering*, ASCE, 111(3), 302-318.

Harrop- Williams, K. (1989). "Arch in soil arching." *Journal of Geotechnical Engineering*, ASCE, 115(3), 415-419.

Lam, S.S.S., Yeung, A.T., and Ng, A.K.L. (2011). "Field-scale evaluation of non-destructive underground void detection techniques." *Proc., 2nd International Conference on Utility Management and Safety*, Hong Kong.

Terzaghi, K., Peck, R.B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*, 3rd Edition. John Wiley & Sons, New York, New York.

Yeung, A.T., and Ng, A.K.L. (2009). "Non-destructive detection of underground voids." *Proc., 1st International Conference on Utility Management & Safety*, Hong Kong, 253-260.