The investigation of underground streams in a weathered granite terrain in Hong Kong

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ABSTRACT: This paper describes the investigation of a large cavity ('sinkhole') discovered on a hillside in Hong Kong. Such collapses are unusual in weathered granite terrain, as they tend to be more commonly associated with limestone or salt deposits. The discovery prompted a major investigation into the nature and origin of the cavity partly because of concern about the stability of the site which overlooks a road in the urban area. The cavity together with the associated underground streams was characterised using a broad range of ground investigation techniques. These included geological and geomorphological mapping of the cavity and surrounding area, the drilling of several boreholes and the use of geophysics. Boreholes were put down using Mazier sampling with foam flush to obtain good quality undisturbed samples. Geophysical investigations included gravity surveys, ground penetrating radar and resistivity surveys. The cavity was shown to have collapsed into a system of underground streams running roughly parallel downhill at a depth of several metres below ground surface. Graded and layered sediments found in groundwater monitoring 'buckets' that had been installed in standpipes close to the cavity several years earlier provided evidence of intermittent subsurface stream flow. The findings from the investigation suggest that the development of the underground stream system at this site is linked to a large ancient landslide that did not fully detach.

1 INTRODUCTION

This paper describes the investigation of a large cavity that appeared in a hillside in Hong Kong in 2002. The cavity was roughly circular, 3 metres across and about 7 metres deep. A footpath partly collapsed into the cavity but there were no other immediate consequences. The site of the cavity was about 10 metres up-slope of Yee King Road (Figure 1) and there were concerns that the cavity might be part of an extensively developing instability which might affect the road and the adjacent slopes in the event of failure. Several soil nails that had been installed to stabilise one of the cut slopes along Yee King Road were exposed within the cavity. The exposed soil nail reinforcement bars were largely un-grouted, and there were concerns regarding the integrity of the soil nails in this and the adjoining slopes (Figure 2). The fairly large cavity was an unusual and possibly unique phenomenon within granite terrain in Hong Kong. It was therefore important to try to better understand its provenance so that the potential for other similar collapses could be assessed and necessary actions taken to safeguard public safety.

The Hong Kong SAR Government implements a systematic landslide investigation programme with the assistance of landslide investigation (LI) consultants managed by the Geotechnical Engineering Office (GEO). Serious landslides and other geotechnical incidents are investigated in detail either using GEO's in-house teams or through GEO's LI consultants. The investigation of the Yee King Road incident was carried out under a LI Consultancy undertaken by Halcrow China Ltd. and is reported in detail in Halcrow (2003).

Figure 1. Overgrown hillside on which the cavity appeared.

2 FIELD RECONNAISSANCE

Inspection indicated alluvial deposits at the bottom of the cavity together with man-made detritus such as plastic bags. It was surmised that the cavity was probably formed as a result of collapse of the ground into an underground stream. The stream was not flowing at the time of inspection and part of the downstream outlet had been choked by fallen debris. The cavity was mapped on one side as highly decomposed granite (HDG) containing corestones up to 2 m of slightly or moderately decomposed granite. A distinct, steeply dipping boundary ran between the HDG and a zone of darker, mostly colluvial soil containing large boulders. Some zones of gravel and sand identified were probably alluvial in origin. At a depth of about 3 m a rounded cobble of volcanic rock was sampled from the alluvium which was strange, given that there are no known volcanic rocks up stream of the cavity (Figure 3). The upper part of the cavity was in fill, probably associated with squatter occupancy of the area in the recent past. It was postulated that the cavity probably intersected a boundary between *in situ* ground and an ancient stream channel choked with colluvium.

Figure 2. Cavity being inspected. Note exposed soil nail and grout that spilled down the side of a boulder.

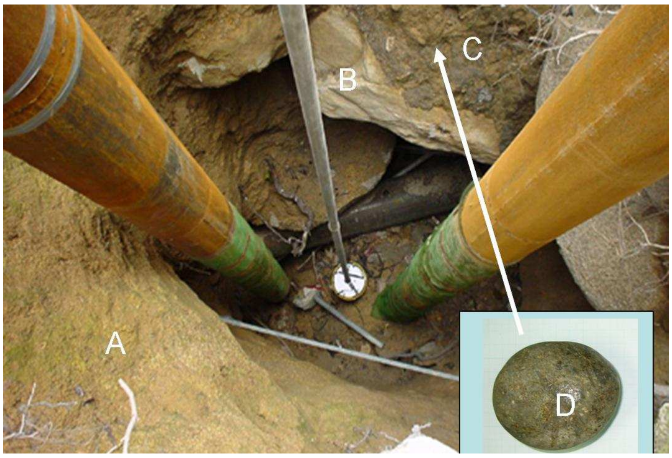

Figure 3. View down the cavity with various casings for subsequent instrumentation. A is insitu HDG, B colluvial boulders, C a zone of alluvium containing a volcanic "erratic" (D).

3 DESK STUDY

Developments in Hong Kong have been well documented since the mid 19th century with topographic maps, terrestrial and aerial photographs and even paintings providing useful sources of information for current-day investigations. For this study old photos proved to be very useful in establishing the site history (e.g. Figures 4 and 5). Other desk study sources included old maps, current geological maps and the field sheets used in compiling geological maps together with the logs of several boreholes, some of them put down for design of stabilisation works on adjacent slopes. Extremely useful data were also obtained from the construction records of Yee King Road and nearby structures together with detailed observations that were made during those works. In particular, observations and photographs taken during the construction of the bus station below the road were helpful in developing a geological and landslide mechanism model for the site and the series of underground streams through the hillside (Figure 6). These documents were generally obtained without much difficulty from various Government Departments.

Figure 4. Temple at foot of slope in 2002.

Figure 5. Same temple in 1869 - then close to the coastline.

Figure 6. Apparently undisturbed weathered granite profile with corestones exposed during 1987 construction of bus station below Yee King Road, Wedge of possible colluvium in line with the subsequent Cavity above the road.

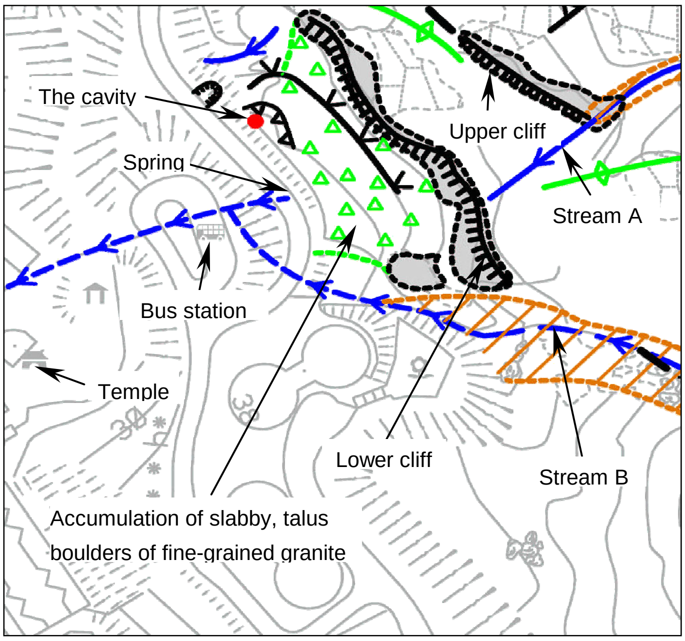

Figure 7. Geomorphological map of main features.

Figure 8. Examination of massive, almost un-jointed, vertical Lower Cliff to rear of area including the cavity.

Figure 9. Layered soil sample in Halcrow Bucket.

4 FIELD WORK

Field mapping was undertaken to establish the key geomorphological and geological features at the subject site (Figure 7). In particular two extensive rock cliffs were identified above the relatively flat, boulder-strewn area surrounding the cavity. The Lower Cliff (Figure 8) consists of medium-grained granite over-lain by fine-grained granite and the contact is almost horizontal. The Upper Cliff consists of all fine-grained granite. Many of the large slabby boulders in the area near the cavity in Figure 7 are fine-grained granite and appear to have been displaced vertically downwards by tens of metres from their original in-situ outcrop locations, with little tilting. It was postulated that this landform was essentially the result of erosion of the more weathered, coarser-grained granite, underlying the fine-grained granite and essentially undermining the fine-grained granite.

Direct evidence for active suffosion of the ancient stream channel at the time of investigation was found through observation of sediments in a series of 'Halcrow buckets' (groundwater level monitoring 'buckets') that had been installed in standpipes dur ing a ground investigation close to the cavity in 1996 (see Figure 9). These sediments were layered and graded and indicated several distinct events involving pulses of sediment-laden water passing from a high level, down the standpipe, past the buckets and exiting at the deeper stream level. Figure 10 is a schematic representation of the likely hydrogeological condition.

Natural erosion pipes had been observed below Yee King Road during the construction of the bus station (Figure 6), and a major spring issues below, in line with an incised stream channel (A) that is truncated at the Upper Cliff and disappears underground at the Lower Cliff (Figure 8). Water could be heard running underground at that location.

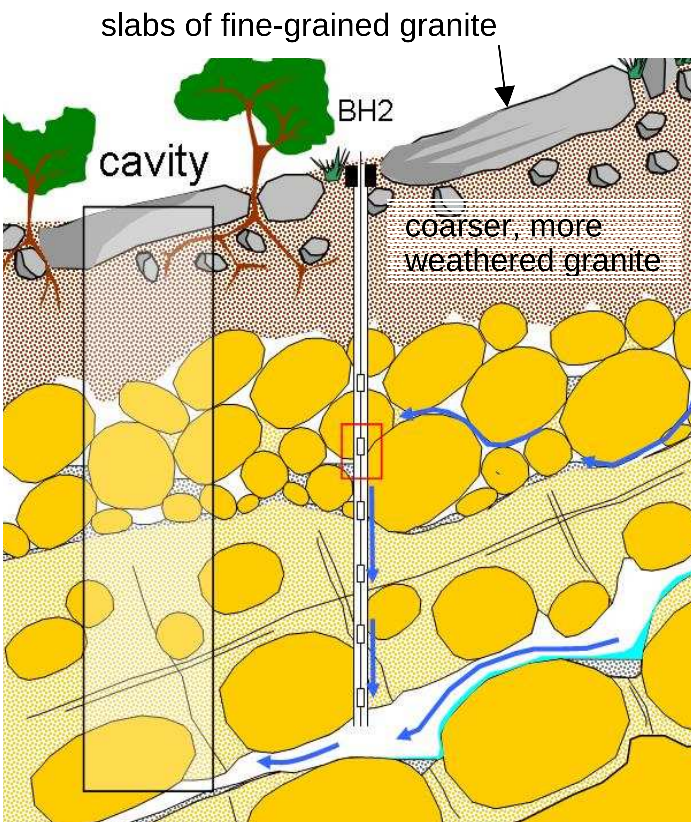

Figure 10. Hydrogeological model for the cavity.

5 GEOPHYSICS INVESTIGATION

Various geophysical techniques were used to search for the suspected underground stream sources. The microgravity survey was of limited use because of the irregularity of the ground surface and ground radar survey below Yee King Road was not effective due to inadequate penetration of the signals and insufficient contrast of the return signals to define the ground profile. Resistivity survey by comparison allowed zones of high resistance (e.g. air voids) to be traced across the hillside. Basic data and their interpretation as a model of the underground stream system are illustrated in Figures 11 and 12. The resistivity survey was carried out in areas below the Lower Cliff and between the Upper and Lower Cliffs in the winter, during which time water vapour was noted to be issuing from several outlets between the boulders strewn across the area around the cavity.

The air issuing from these vents was measured to be about 10°C warmer than the air temperature. Most of the vents were observed to be roughly in a straight line between the location where Stream A disappears into the ground (viz. at the edge of the Upper Cliff), and where the spring was issuing below the bus station below Yee King Road (Figure 7). Dye tracer and saline water tests were successfully conducted to confirm the connectivity between (mainly subsurface) sources and the streams below the site.

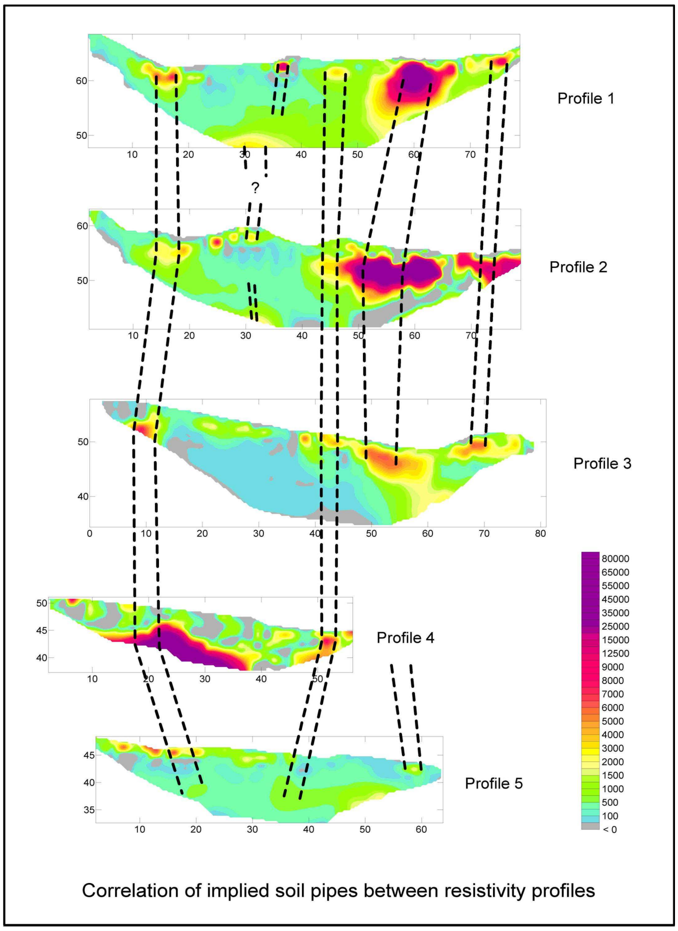

Figure 11. Resistivity data across the slope indicating likely locations of voids.

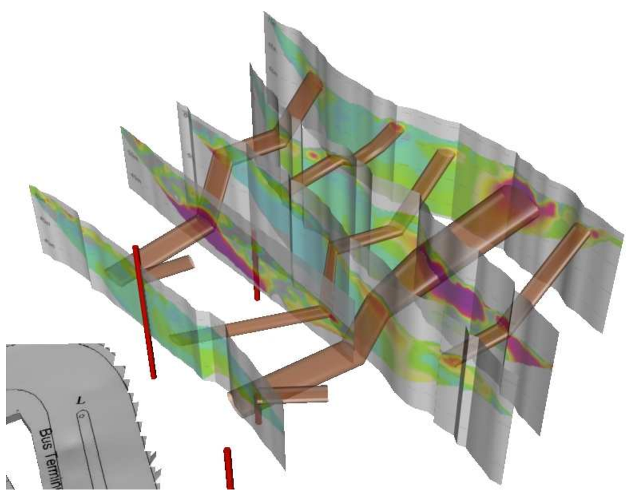

Figure 12. Interpreted 3D model of site with underground streams.

6 GROUND INVESTIGATION

To investigate the extent of disturbance associated with the underground stream system, a series of trial pits and boreholes were put down. The trial pits helped to confirm the extent of colluvium and weathered *in situ* rock adjacent to the cavity.

Boreholes were drilled to establish the nature of the rock profile at the cavity and at nearby locations, especially targeting at the probable stream locations as identified by the geophysical surveys. It was decided to use Mazier sampling with foam flush, which has been demonstrated to give the best recovery potential in weak weathered rock profiles (Phillipson & Chipp, 1982).

Figure 13 shows foam flush drilling in action. One of the key questions to be addressed by these boreholes was whether there were signs of disturbance at depth below the stream levels. Deep natural erosion pipe systems have been identified in Hong Kong, especially in association with large landslides (Hencher, 2006). All Mazier samples were split and logged carefully but little evidence was found of any disturbance or the existence of streams below the levels as identified by geophysics and confirmed through lack of core (and loss of drilling flush) as compared with core loss in the drillholes. The largest void discovered by drilling was about 3.15 m vertically between 5 and 8 m depths. CCTV cameras were used to explore some of the cavities down the boreholes. A cross section across the site, developed on the basis of all available data, is shown in Figure 14.

Groundwater monitoring using automatic water level monitoring devices has been carried out since then with the base groundwater level showing a typical storm response of up to 3 m, which corresponded to rainstorm events with return periods of less than 2 years. A storm response in excess of 5 m was observed at one location.

Figure 13. Foam drilling at Yee King Road.During the 2002 investigation, most of the drillholes showed no groundwater at the levels of the underground streams.

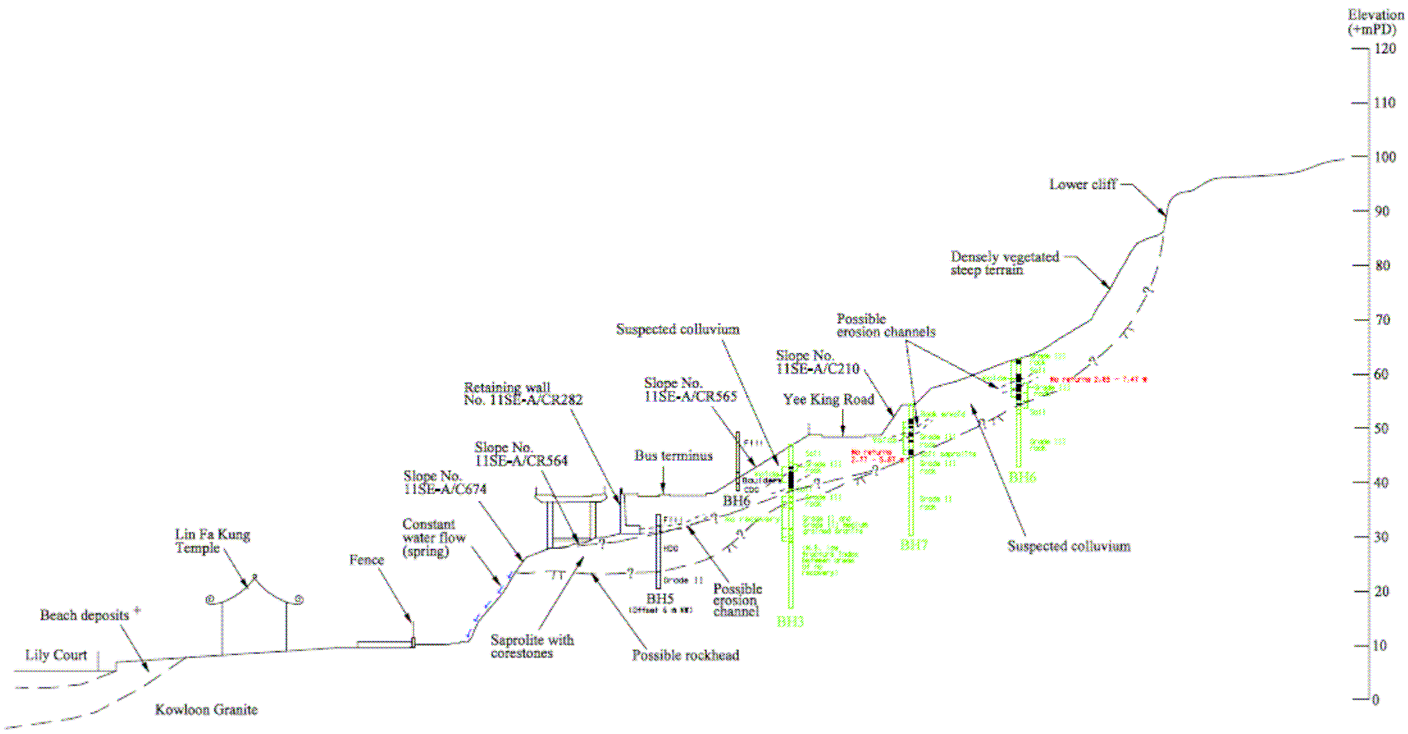

Figure 14. Cross section through site. Cavities identified in boreholes are indicated

7 DISCUSSION AND CONCLUSIONS

Subsurface erosion due to concentrated underground water flow is quite common in weathered rock and colluvial terrain in Hong Kong and the adverse effect on slope stability has long been recognised (Brand et al, 1986). Formation of sizeable cavities by subsurface erosion however occurs relatively rarely in rocks such as weathered granite (Twidale, 1982; McFarlane & Twidale, 1987; Panno et al, 1994) and such cavities are generally termed “pseudo-karst” to distinguish them from the more common karstic cavities brought about by dissolution in rocks such as limestone and rock salt (Younger & Stunnell, 1995).

It was concluded from the present investigation that the cavity identified in 2002 was the result of collapse of material forming its roof into a natural stream system at depth. The cavity had probably been partly open previously and may have been used by squatters as part of a soak-away drainage system or, just possibly, as a well in the past. The presence of a rounded erratic volcanic cobble in the alluvium 3 m below ground surface led the investigating team to postulate that it might have been brought to the site by man in pre-historic times, but there was no other evidence for such long-term occupancy of the site.

The underground stream system is well developed and there are numerous natural vents to the ground surface. One (at least) surface ephemeral stream disappears underground at the Lower Cliff some distance above the area of the cavity, before emerging at the bus station below the site.

The development of the underground stream system at this site is probably linked to a large ancient landslide that did not fully detach. In terms of geomorphological development, it is postulated that the area below the Upper Cliff was probably the site of a large but shallow landslide of some considerable age as illustrated in Figure 14. The shallow nature of the landslide was indicated by the limited depth of underground streams, the lack of disturbance in the weathered rock below that level (as observed from detailed logging of the 100% recovery Mazier samples), and the lack of disruption in the weathered rock shown in construction photographs from 1987, below the site. When the landslide occurred, surface streams migrated underground, exploiting the disturbed ground. Considerable erosion has taken place within the highly decomposed coarser-grained granite undermining the less weathered, finer-grained granite, large slabs of which probably dropped in position by up to some 20 metres.

In terms of the investigation, all the ‘conventional’ approaches have proved useful. Desk study was important for establishing the history of the site and possible anthropogenic influence on the development of the cavity. Resistively surveys proved effective in locating voids (as found previously by Panno et al, 1994) and allowed a large area to be investigated relatively cheaply and the later ground investigation to be more focused. Careful drilling, aimed at 100% core recovery followed by detailed examination of all cores, observation on flush returns and the use of CCTV cameras all contributed to the development of a reliable ground model for the site.

Following the discovery of defective soil nails within the cavity, the cut slope adjacent to the cavity, as well as all the other slopes upgraded under the same contract, were investigated in detail and all defects found were rectified by the contractor of concern at his own cost.

8 ACKNOWLEDGEMENTS

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