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Site characterization of the area surrounding a sinkhole, a case study

M. P. Magagula[1], AMSAICE and G.R. Wardle[1], FSAICE

[1]Jones & Wagener (Pty) Ltd, Engineering & Environmental Consultants, P.O. Box 1434, Rivonia, 2128; PH (+27) 11-519-0226; FAX (+27) 11-519 0201; email: magagula@jaws.co.za or mondli1937@live.com, wardle@jaws.co.za

ABSTRACT

In 2014, a sinkhole occurred below a fuel pipeline at Tarlton International Speedway, near Johannesburg in South Africa. Following the sinkhole collapse, visual inspections were conducted to determine the direction of the throat and the probable causes of the sinkhole. Emergency backfilling of the sinkhole was undertaken, followed by site characterisation of the area comprising geophysical gravity surveys and percussion borehole drilling. The boreholes were drilled on the gravity highs and lows as per the results of the gravity surveys. The gravity survey was able to establish the shallow and deep weathering profile of the dolomite rock head, but was unable to define the cavity or subsurface receptacle. Additional boreholes were drilled in the perceived visual direction of the sinkhole throat observed from the initial inspection. This drilling defined a cavity that extended beyond the surface opening of the sinkhole. The investigation confirmed the importance of using more than just one method of ground investigation to compile an accurate geotechnical model of the site. The true extent of the subsurface cavity could only be discovered through exploratory drilling based on observations of the throat itself soon after the sinkhole was discovered. Had the cavity, that extends beyond the surface opening of the sinkhole, not been identified, it would have resulted in an underestimate of the extent and cost of the remedial works.

Keywords: Dolomite, Investigation, Sinkhole, Geophysics, Boreholes.

1 BACKGROUND

Gauteng is South Africa's smallest province, but is the country's economic hub and has drawn a large percentage of the country's population to seek work and residence on its land. With the continued growth of the province's population, real estate development is forced more and more onto dolomitic land. The dolomites are prone to sinkhole formation and are recognised as one of South Africa's main 'problem soils', Wagener (1985). This has prompted extensive research into dolomite and the development of a South African National Standard to address development on dolomitic land, i.e. SANS 1936:2012.

Dolomite is a chemical or biochemical sedimentary rock, comprising primarily of the mineral dolomite which consists of calcium magnesium carbonate $CaMg(CO_3)_2$ and secondary Silica known as chert. Although dolomite has many practical uses such as aggregate in concrete, the one drawback is that dolomitic rock is highly susceptible to solutioning by even slightly acidic water. Acidic water refers to water that has been subjected to dissolution with CO_2 in the atmosphere, with the resultant reaction creating weak carbonic acid (H_2CO_3). As this slightly acidic water infiltrates the ground and mixes with the ground water system, it causes weathering of the dolomitic rock. The rock subsequently breaks down into soluble and insoluble by-products. This chemical process is represented as follows: $CaMg(CO_3)_2 + 2H_2CO_3 \rightarrow Ca(HCO_3)_2 + Mg(HCO_3)_2$ (WRC, 2003). Solutioning of these by-products results in sub-surface cavities in the rock profile. In areas with a low or deep water table i.e. a water table below the solution cavity, where wash out of the soils within the overburden has resulted in the development of a meta-stable arch above the throat of the cavity, the downward migration of water can weaken the arch and trigger the formation of a sinkhole. In areas with a shallow water table, i.e. water table above the cavity, subsequent drawdown of the water table can similarly trigger the formation of a sinkhole. Figure 1 illustrates the idealized sinkhole formation mechanism in a low groundwater table environment as contained in SANS 1936. In Figure 1 the sinkhole is triggered by a leaking wet service. Leaking services are by far the dominant cause of sinkhole formation in built-up urban areas, whereas lowering of the water table as a result of farming and/or mining activities is often the trigger in rural areas. South African research shows that 96% of sinkholes and subsidence events recorded were man induced and resulted from the absence of appropriate risk mitigating measures.

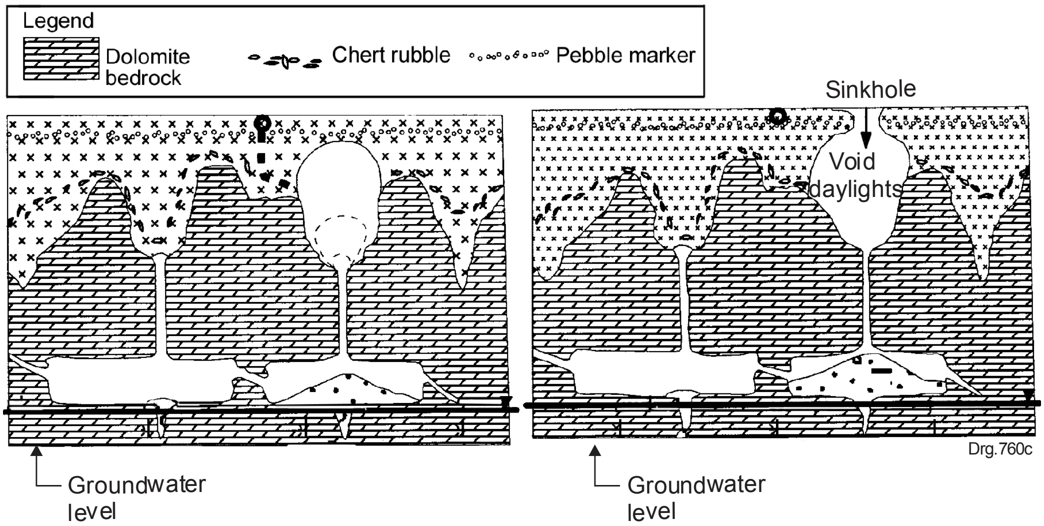


Figure 1. Sinkhole Formation (SANS 1936)

2 INTRODUCTION

In April 2014, a sinkhole formed below a fuel distribution pipeline in the Tarlton agricultural region of Gauteng. The regional geology comprises Malmani Subgroup dolomites of the Chuniespoort Group, Transvaal Supergroup. The sinkhole (left hand side of Figure 2) was about 10m to 12m in diameter at ground surface and was estimated to be about 7m deep on average. The sidewalls of the sinkhole were near-vertical with the overburden comprising mainly silty sand with fine chert gravels and ferricrete/manganocrete nodules.

A preliminary site inspection of the sinkhole was undertaken to determine the possible causes of the sinkhole, as well as to assess any damage to the fuel pipeline. During the preliminary inspection, it was noted that the fuel line had neither ruptured nor had incurred any damage, thus was most likely not the reason for the sinkhole formation. Also noted during the preliminary inspection, was that at the southern end of the sinkhole, there was an approximately 1.5m diameter “throat” that disappeared from view in a southerly direction almost immediately below the pipeline (shown in the right hand side of Figure 2). It was through this throat and lower-lying cavities that the ground that originally occupied the volume of the sinkhole had been eroded.

(a) *(b)*

Figure 2. (a) Sinkhole; and (b) 1.5m Sinkhole Throat

For safety reasons as well as to prevent water ingress into the sinkhole, which would have resulted in material washing away through the sinkhole throat, thus increasing the size of the sinkhole. Emergency backfilling of the sinkhole was recommended and carried out shortly after the initial inspection. The backfilling was a short term solution as saturation of the backfill from surface water ingress would be likely to cause the soil to start settling under its own weight and drag the pipeline down.

3 SITE CHARACTERISATION

3.1 Initial Site Visit

The initial site visit, whilst the sinkhole was open, proved to be invaluable, as information obtained from the site visit turned out to be the biggest contributor to the planning of the geotechnical investigation and subsequent remedial works.

During the site visit it was also discovered that the probable cause of the sinkhole was an existing trench, termed a “security trench”, dug to prevent vehicles entering the area on the property on which the pipeline is located. The trench facilitated collection and ponding of surface water run-off, thus resulting in infiltration into the underlying subsoil and ultimately leading to the collapse of the overburden.

Following the inspection, the sinkhole was immediately backfilled with loose spoils placed as an emergency measure for (i) safety; (ii) to prevent further concentration of surface water; (iii) to prevent enlargement of the sinkhole by choking the throat; and (iv) to provide support to the fuel line. Upon re-inspection of the site at a later stage, it was discovered that consolidation of the fill had resulted in a slight depression of the surface.

3.2 Gravity Surveys

3.2.1 Initial assessment of the site

The SANS 1936 standard stipulates that physical geotechnical investigations on dolomitic land should be preceded by a gravity survey of the area. This portion of the investigation was undertaken by a geophysicist. A total of 156 gravity stations were proposed, and data was acquired on a 180m x 165m area using a 15m grid spacing. An additional 36 stations were added in close proximity to the sinkhole on a 7,5m grid spacing to provide more detail in this area. The gravity measurements were recorded using a Scintrex CG-5 gravimeter. The gravity station coordinates and elevations were surveyed using a Trimble RTK GPS system.

The product of the gravity survey is a residual gravity anomaly map obtained by subtracting the regional influence from the measured values. The regional gravity map was obtained using a gridding algorithm where each cell is influenced by a large number of surrounding measurement points. The purpose of this is to remove deeper gravity variations and to provide a more detailed and shallower view of density variations. High residual gravity values are indicative of shallow bedrock, typically pinnacles of hard dolomite rock. Low residual gravity values, on the other hand, are indicative of deeply weathered grykes or valleys between the pinnacles, or subsurface cavities in the rock mass.

Figure 3 illustrates the results of the residual gravity survey highlighting three anomalies detected namely; Anomaly A – a very prominent gravity low, Anomaly B – a gravity low and Anomaly C – a relatively high gravity feature.

From Figure 3 it can be seen that there was no defined gravity low in the immediate area of the sinkhole that could be associated with a cavity. However, anomaly A suggested that, if anything, the cavity would be expected on the south western side of the sinkhole. A decision was taken to investigate this anomaly and the area immediately around the sinkhole by drilling percussion boreholes. It was clear that it would take an assimilation of the gravity maps, borehole information, as well as observations during the initial site visit, in order to properly classify the area.

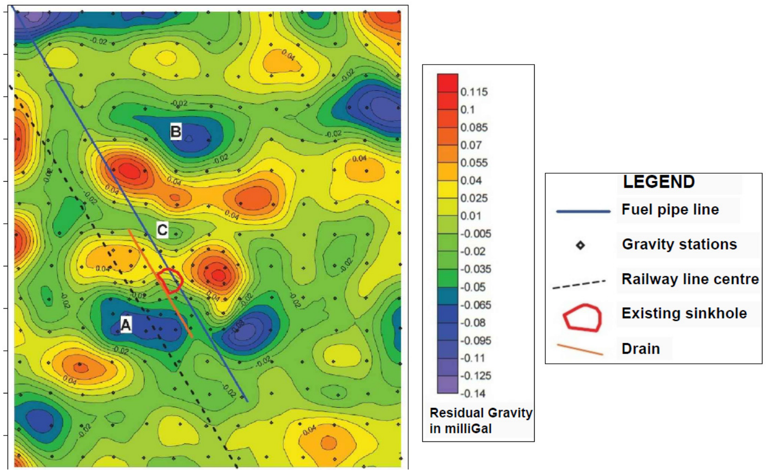


Figure 3. Residual Gravity Survey

3.3 Aerial Photo Interpretation

To better develop the geotechnical model for the area, aerial photograph interpretation (API) was applied. The API made use of 1:30 000 stereo aerial photographs flown in August 1968 and issued by the Government Printer. API is used to delineate general geological features/contacts, terrain units and linear features such as faults and dykes. A terrain unit defines a specific geomorphological landform within the broader area topography where similar geological conditions are present. Similar terrain units generally exhibit similar soil profiles and consequently geotechnical parameters.

The API indicated that, within the area of the sinkhole, a defined linear depression is evident and has been there since 1968. The main section of this depression conformed well to the gravity lows recorded during the gravity survey as shown on Figure 4. The depression is characterized by a very gentle gradient that would typically not have resulted in excessive concentration and infiltration of surface water.

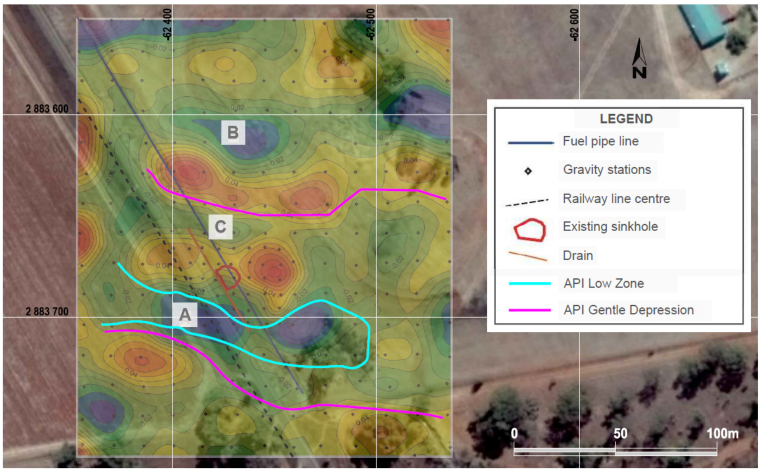


Figure 4. API Interpretation

3.4 Percussion Drilling

3.4.1 The drilling campaign

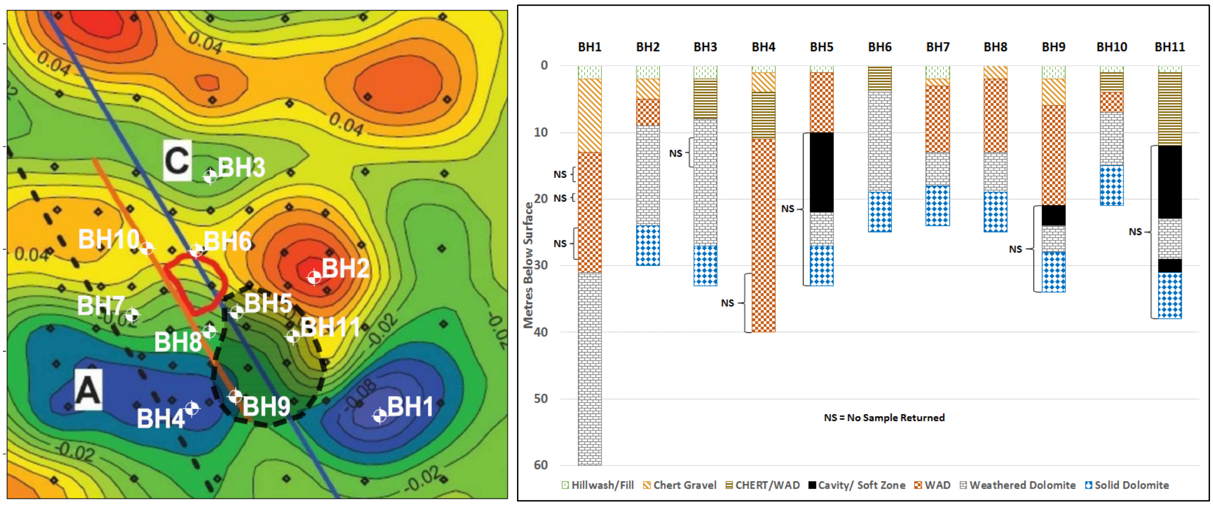
As shown in Figure 5, eleven percussion boreholes were drilled during the investigation. Boreholes BH1 to BH4 were drilled primarily for the purpose of ‘proofing’ the results obtained from the gravity surveys. Boreholes BH5 to BH8 were drilled around the perimeter of the sinkhole. Based on the results of these initial boreholes, three additional holes were drilled, i.e. BH9 to BH11.

The depth of drilling was determined in accordance with the guidelines of SANS 1936-2 which requires boreholes to be drilled into dolomite bedrock on gravity high anomalies to determine the shallowest dolomite bedrock depth, at least 6m into hard rock dolomite or 15m into non-dolomitic rock and a representative selection of boreholes to at least 60m if dolomite bedrock is not confirmed at shallower depth.

The drilling of the boreholes was conducted by geotechnical contractors and was carried out using a 116mm (4.5”) diameter down-the-hole air percussion hammer. Representative samples of drilling chips were collected at 1m intervals and placed in marked plastic bags. Drilling observations were recorded on driller’s log namely: depth, drilling rate per meter, water strikes, addition of water or drilling foam if required, air loss, potential cavities, sample return and hammer tempo.

3.4.2 Drilling Results

Following logging of the chip samples by an experienced engineering geologist, a profile log was compiled for each borehole including the drilling parameters. Figure 5(a) shows the borehole positions as well as the approximate position of the cavity, whilst Figure 5(b) shows a simplified profile summary for each borehole.



(a) (b)

Figure 5. (a) Borehole Positions; and (b) simplified profile of material units within each borehole

From Figure 5 it is evident that the gravity survey was able to identify the shallow (BH3, Anomaly C) and deeply weathered profiles (BH 4, Anomaly A) in the bedrock. However, it was not able to identify the cavities/soft zones around the sinkhole identified in BH5, BH9 and BH11.

Based on the drilling information the approximate extent of the cavity and its position relative to the sinkhole was established. Figure 6 illustrates the extent of the sinkhole and the approximated locations of the underlying cavities.

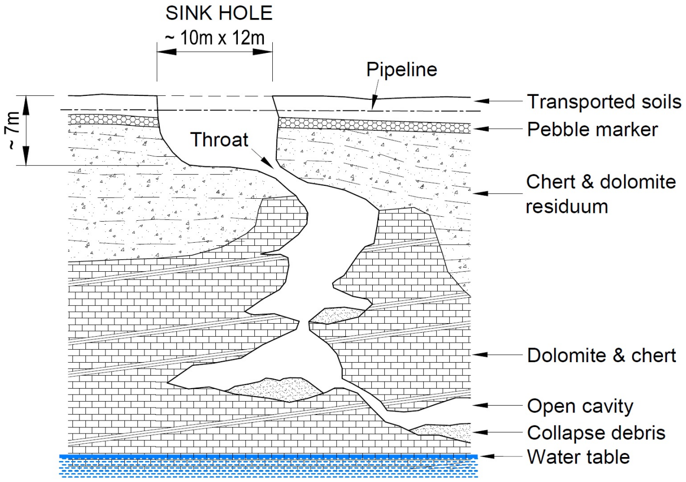


Figure 6. Sinkhole and Underlying Cavities

4 DISCUSSION

The detailed geotechnical investigation which followed the sinkhole collapse made use of a range of available methods recommended by the SANS 1936 documents. Each method contributed to the understanding and development of a comprehensive geotechnical model of the site and the sinkhole mechanism. The initial site inspection, shortly after the sinkhole was noticed, provided invaluable clues as to the location of the sub-surface cavity and the trigger for the sinkhole collapse. Gravity surveys identified the variable shallow and deep rock head topography that is so characteristic of the pinnacles and grykes in the dolomites. Physical borehole drilling, guided by the gravity anomalies, confirmed the locality and extent of the cavity/ies around the site and thus helped facilitate the final remedial works. The API revealed that the naturally occurring depressions on site did not result in the excessive ponding of surface water and that the ponding of surface water was as a result of manmade interventions, in this case the “security trench”.

An interesting and unexpected observation of this project was the offset and asymmetrical location of the surface expression of the sinkhole compared to the sub-surface cavity. In January 2004 a 20m deep, 30m wide sinkhole formed in Bapsfontein located in the east of Johannesburg. The sinkhole was also asymmetrically located from the throat; this shows that a throat asymmetrically located from the sinkhole is not a unique feature to the Tarlton Sinkhole. Most illustrations of a sinkhole model, e.g. SANS 1936, show the sinkhole developing directly above the mouth of the cavity. Recent centrifuge research at the University of Pretoria (Jacobsz, 2016) confirms the vertical chimney-like nature of the propagation of subsurface erosion mechanisms in cohesionless soils above the water table. It is important that we further develop our understanding of these mechanisms and the reasons for the sinkhole to develop off-centre with respect to the mouth or throat of the cavity.

Remedial works of the sinkhole are not discussed in this paper, suffice to mention that compaction grouting of the sub-surface void was carried out to prevent a repeat occurrence of the sinkhole. As part of this exercise, the “security” trench was backfilled and the surface levelled off to allow surface water to pass over to a nearby concrete-lined drainage channel.

5 CONCLUSIONS

It is concluded that no single investigative method can be relied upon to provide a full geotechnical characterisation of a site, especially a site with complex geology or problem soil conditions. Several methods, each acting like a piece in a puzzle, have to be assimilated to compile the full picture. In addition, this case study has also shown the value of experienced geotechnical practitioners attending to a site inspection as soon as possible after the event of the sinkhole occurrence. Had the site not been properly characterised, only partial remediation of the problem ground condition would have been achieved by the remedial works. This case study highlights the importance of using geophysical methods in conjunction with visual inspections and physical explorations (boreholes).

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