Case study - The rehabilitation of a sinkhole under hazardous conditions

F. Van der Berg, T. Kubayi & T. Green
Jones & Wagener, Johannesburg, South Africa

ABSTRACT: The design and remediation of two sinkholes that formed within the road reserve of a major highway in Gauteng is summarised herein. Due to the location of the sinkholes underneath low hanging powerlines, and the proximity of the sinkholes to the road, somewhat unconventional methodologies were required to address the particularly restricted and hazardous nature of the site. This paper details the remediation strategies utilised when conventional strategies are not possible. The paper highlights the challenges encountered during the design and implementation phase and explores the solutions that were obtained through innovative collaboration between the engineering team and the appointed contractor.

1 INTRODUCTION

Following a period of heavy rainfall, a sinkhole formed in the road reserve of one of the major national highways in the Gauteng province of South Africa. The sinkhole was up to 15 m in diameter and compromised the structural integrity of the road, necessitating the two slow lanes to be closed, which in turn had a very negative effect on the traffic flow.

The first step in the rehabilitation process was to complete a geotechnical investigation according to SANS 1936 part 2 as published by SABS (2012) to find the extent of the area where rehabilitation was required. This included zoning of the area according to its Inherent Hazard Class (IHC).

Following the investigation, the remedial measures were designed, taking into consideration certain site-specific hazards.

The remediation method was implemented as a 2 phased approach, an 'initial remediation' phase and a 'final remediation' phase. The initial remediation comprised using grout bags to plug the throat of the sinkhole and then filling the sinkhole with low strength concrete. This stabilised the affected area sufficiently for the final rehabilitation to commence. The final rehabilitation comprised drilling percussion boreholes and applying compaction grouting to these boreholes to a depth of 25 m.

2 INVESTIGATION

2.1 *Geotechnical investigation*

The first phase of the sinkhole rehabilitation project comprised a geotechnical investigation to verify the extent of the proposed remediation design. While detailed analysis of the investigation and results obtained is outside of the scope of this paper, the methods used are briefly discussed below.

2.1.1 *Geophysical and gravity surveys*

Geophysical surveys that were conducted on site included: Electrical Resistivity Tomography (ERT), Multichannel Analysis of Surface Waves (MASW), Refraction Seismic Method, and Ground Penetrating Radar (GPR). A gravity survey was also conducted on site, which identified zones of strong gravity gradient, and zones with high or low gravity.

The results of both the geophysical and gravity surveys were used to scope the intrusive percussion borehole drilling investigation.

2.1.2 *Percussion drilled boreholes*

Following the geophysical and gravity surveys, percussion boreholes were drilled at 71 positions. The holes were drilled to a depth of 60 m or until 6 m of competent bedrock had been found, in compliance with SANS1936. Chip samples were taken at 1 m intervals and were logged on site by a qualified engineering geologist in accordance with the standard procedures proposed by Brink & Bruin (1990).The water level in the boreholes were monitored for 24 hours after the hole had been completed.

While the boreholes were characterised by extreme variability, which is not uncommon in dolomite, the following stratigraphy was typically encountered:

- Fill material from surface to a depth of 1 to 7 m.
- Dolomite residuum comprised highly weathered chert, interbedded chert and WAD, or thick layers of WAD. The highly weathered chert varied from 1 to 28 m thick, the interbedded chert and WAD varied from 1 to 50 m thick, and the WAD varied from 1 to 39 m thick.
- Dolomite bedrock was present in the majority of boreholes from a depth of 4 to 45 m.

Zones with very low penetration rates were encountered across the site, with the most severe boreholes having penetration rates less than 10 sec/m from a depth of 3 m to a depth of 47 m.

Zones with very low penetration rates, coupled with air loss, sample loss and no hammering, which are indicative of cavities or very soft WAD material, were picked up in 8 of the 71 boreholes from average depths of between 15 m to 30 m below ground level.

2.1.3 *Determination of hazard classification*

Using the borehole drilling logs discussed above as well as the geophysical and gravity survey results, the site was divided into zones where the dolomite was similar (refer to Figure 1). For this to be completed, the IHC of every borehole had to be allocated, and boreholes with similar IHC's had to be grouped together.

The IHC was split into three zones, namely:

- Zone A (IHC 3 / 4)
- Zone B (IHC 6)
- Zone C (IHC 7 / 8)

According to the SANS1936 standard, for a land use designation of IN1 for national and regional roads, Zone A and Zone B was classified as a D3 designation and Zone C was classified as a D4 designation. The D3 designation had a medium to high susceptibility for the development of small to medium diameter sinkholes (2 to 5 m diameter). Due to the nature of the road pavement design, the formation of such a sinkhole was unlikely to cause a catastrophic failure, but rather limited damage to the road. The D4 designation however had a high susceptibility for the formation of very large sinkholes with a diameter in excess of 15 m. This zone therefore was considered to be a very high risk to the road, as a sinkhole of this size would have likely caused a catastrophic failure.

It was therefore recommended that Zone C be fully rehabilitated; it was not deemed necessary to rehabilitate Zones A and B.

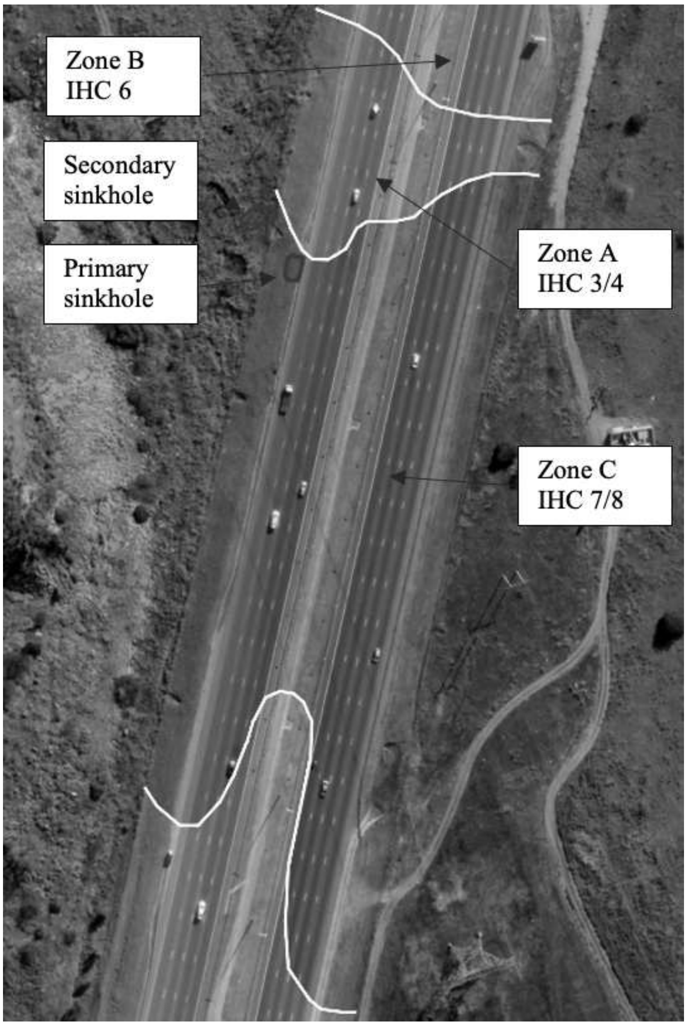


Figure 1. The determination of the area that requires remediation

2.2 *Challenges encountered*

The following site-specific challenges were identified during the investigation phase that would affect the chosen method of remediation:

- Large portions of the site that required rehabilitation lay directly underneath high voltage powerlines that cross the highway. The presence of these powerlines limited the height of plant to avoid the possibility of arcing of the electrical current. A height restriction of 3.5 m above the road level was implemented, at Eskom's request, to avoid the possibility of arcing.
- The highway had extremely high traffic volumes, with the average daily traffic being in excess of 40 000 vehicles in a single direction.
- The concentration of a cluster of approximately 10 other large sinkholes to the west of the two sinkholes that required remediation made gaining access to these sinkholes challenging. The only safe access could be obtained from the road (refer to Figure 2).

Figure 2. The location of the sinkholes both within the road reserve and outside the road reserve.

3 DESIGN

The remedial solution was split into 2 different phases, namely the initial remediation followed by the final remediation. The purpose of the initial remediation was to stabilise the sinkholes, such that plant and labour could safely enter the area around the sinkholes to complete the final remediation. The final remediation was based on a statistical, risk-based approach. The purpose of the final remediation was therefore not to completely eliminate the possibility of sinkholes forming in the affected area, but rather to reduce this risk as far as practically and economically possible and furthermore, in the unlikely event a sinkhole did form under the highway, limit the damage caused by the formation of a very large sinkhole (>15 m diameter). This would provide warning in the form of cracks and deformation on the road surface should such a sinkhole form, rather than a catastrophic sudden failure leading to loss of life and long-term closure of the highway.

3.1 *Initial remediation*

The initial remediation comprised stabilising the sinkholes themselves such that the final remediation could be implemented. Many different methods exist for the remediation of sinkholes (Kleinhans & Van Rooy 2016; Zhou & Lei 2017). Two options were considered, namely the inverted filter method and the grout bag method. Both options are discussed below.

3.1.1 *Inverted filter method*

The inverted filter method is a widely used method for remediation of sinkholes. This method consists of using boulders or rockfill to block the throat of the sinkhole. Once the sinkhole throat is blocked, the rest of the sinkhole is backfilled with engineered fill to the surface.

While this is a proven and cost-effective method of remediating sinkholes, it was not possible on this site due to the height restriction that made it impossible to use plant typically required for this method. Implementation of this method would therefore have required a conveyor system to deliver the rockfill to the sinkhole, which would have been challenging due to the lack of safe access to the sinkhole throat.

Due to these site-specific challenges, this method was not an appropriate solution.

3.1.2 *Grout bag method*

This method involves placing grout bags into the throat of the sinkhole, and then pumping the grout bags full of grout, thereby blocking the throat of the sinkhole. A capping layer is then poured over the grout bags to create a level platform, following which the sinkhole is filled with soilcrete or low strength concrete.

This option was more attractive, because it did not require tipper trucks or excavators which would exceed the height restriction. Placement of the grout bags into the throat did, however, prove to be a challenge (refer to Chapter 4).

3.2 *Final remediation*

The proposed method for achieving the design intent described above was compaction grouting. This method involves pumping grout into predrilled holes to fill cavities and increase the density of the erodible subsurface soils.

The grout was specified to have a toothpaste like consistency with a slump of 200 mm. The grout was pumped until a specified volume or limiting pressure was reached at depth increments within the percussion hole.

The compaction grouting was to take place in a series of percussion drilled boreholes, set out in a primary and secondary grid, with the secondary grid being in the centre of the primary grid. Both grids had a grid spacing of 5 m. Holes were to be drilled to 25 m or 7 m into hard rock.

Tertiary holes could be added around primary or secondary holes at the Engineers discretion, taking into consideration drilling conditions and grout takes. For holes that require tertiary holes, four tertiary holes would be added, each offset in four directions towards the four different gridlines.

4 CONSTRUCTION

The staging of the two phases was not consecutive but rather concurrent. The initial remediation was completed while the compaction grouting of the final remediation took place in the areas away from the sinkholes.

4.1 *Initial remediation*

The construction of the initial remediation posed many challenges. It was only through extensive collaboration between the Contractor and the Engineer that these problems could be solved effectively.

The grout bags used were 185 gsm Woven Polypropylene bags. The bags had a volume of approximately 1 m^3 with a closed bottom and an open top. The bag had straps at the top and was fitted with a wooden frame to keep its shape when in the sinkhole.

Placement of the bags into the sinkhole was done by attaching ropes to each corner of the bag and hanging the grout bag from wooden cross beams that were placed over the opening of the sinkhole. A cherry picker was used to suspend the grout bags into the throat from above the sinkhole. The bags were carefully placed in the throat of the sinkhole in groups of three or four. Grout was then pumped into the bag using a flexible HDPE pipe. Once the bags were filled, additional bags were placed, and the process was repeated until the throat was blocked. Figure 3 shows the steps of the blocking of the throat with the grout bag method.

Using the method described above, the sinkhole throat was blocked, but many challenges were faced along the way, and it was by no means a simple process. The method was iterative, and adjustments were made throughout the process to optimise it.

Once the throat was blocked, an approximately 2 m thick layer of 20 MPa concrete was cast over the grout bags to serve as a capping layer. The rest of the sinkhole was filled with low strength concrete. For the sinkhole that was directly underneath the road, the low strength concrete was poured to underneath the level of the layer works, and the road was then reconstructed over the sinkhole. The sinkhole that was mostly outside the road reserve was filled with low strength concrete to 2 m below the NGL. The rest of the sinkhole was filled with G7 fill compacted to 93 % Mod AASHTO.

4.2 *Final remediation - Drilling*

Due to the restrictive headroom available on site, regular truck mounted percussion drill rigs could not be used, but rather custom built short-masted percussion drill rigs were used. While the rigs were very mobile and were short enough to safely drill underneath the powerlines, the trade-off was the torque and pull-out forces that these light rigs were able to generate. The drilling conditions on site were extremely challenging, with large pockets of WAD and cavities causing total airloss, and collapse of the boreholes causing the drill rods to get stuck. In some cases, it was necessary to terminate the borehole early, grout the hole and then recommence the drilling through the grout to stabilise weak layers in the upper part of the borehole.

Borehole cameras were used on site to inspect boreholes where the drill rigs were unable to advance further. Being able to identify the reason for the difficult drilling allowed the team to set up specific solutions to different problems, whether it be collapse of the borehole, cavities or low-density WAD material. Two of these borehole photos are presented in Figure 4 and Figure 5 respectively. Figure 4 shows a borehole drilled through rock with the light of the borehole camera illuminating the sidewalls of the borehole, while Figure 5 shows a borehole through a cavity where the light of the borehole camera does not reach the sidewalls of the borehole. The fact that the sidewall of the borehole is not visible in Figure 5 illustrates the size of some of the cavities found on site.

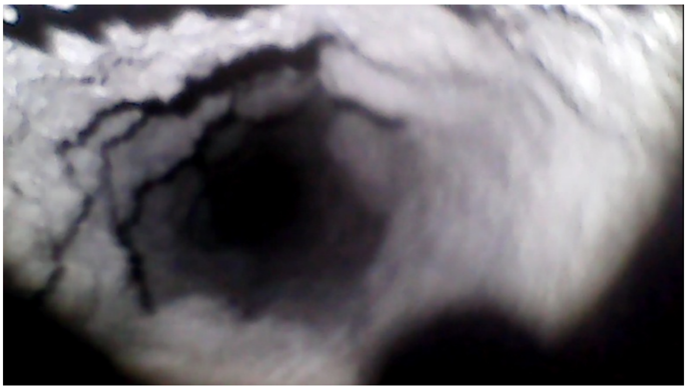
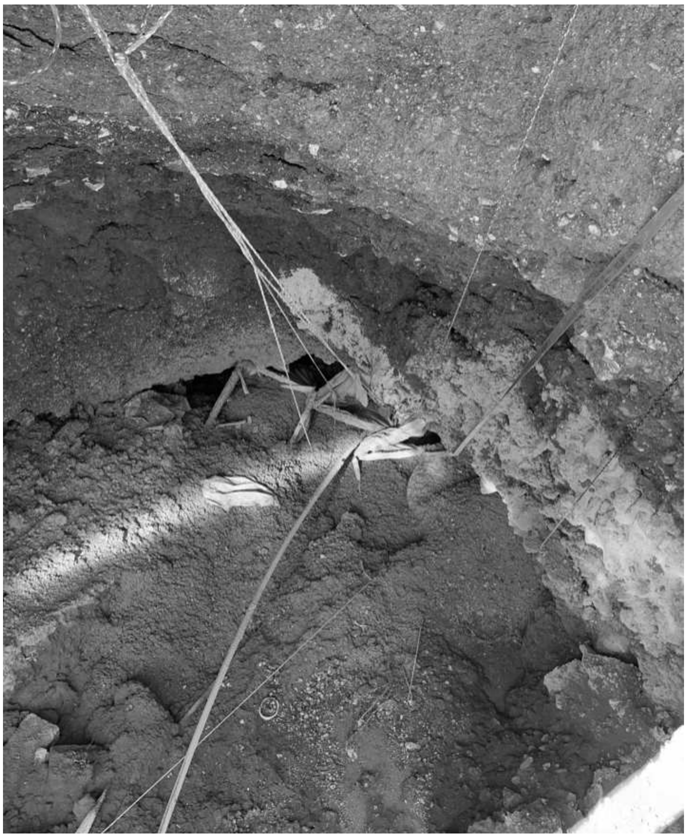


Figure 4. Footage from a borehole in rock.

Figure 5. Footage from a borehole at the entrance of a cavity.

a) Initial placement of the grout bags in the throat of the sinkhole



b) Grout bags after they have been pumped full of grout

c) Placement of additional grout bags

d) Pouring of the capping layer over the filled groat bags

Figure 3. The process of blocking the throat with the grout bag method

4.3 *Final remediation - Grouting*

On multiple occasions, grout material was found in boreholes adjacent to holes that had already been grouted, indicating that the grout had the required consistency to fill cavities or fissures across several metres. On other occasions, while drilling a borehole on the road, dust from the borehole emerged from the open sinkholes adjacent to the road reserve, also indicating subsurface cavities, with approximately 30 m between them, are connected.

The variability of the grout takes is visually represented in Figure 3, which plots the grout takes of each primary grout hole as a peak on the z axis with the x and y axis being the coordinates of the grout hole. The figure shows boreholes with large grout takes surrounded by areas with low grout takes.

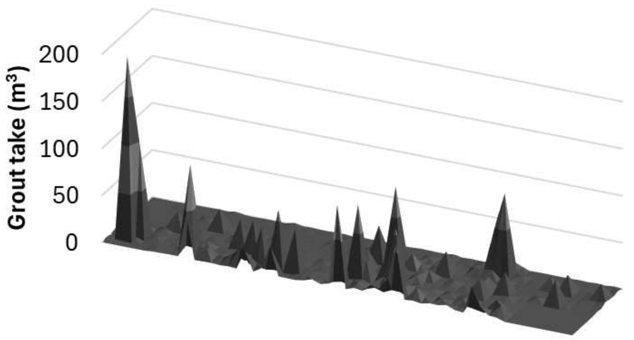


Figure 3 The grout takes of primary grout holes.

The average grout take per hole was 2.7 m^3, but in some cases, a single borehole took in excess of 150 m^3 of grout, indicating the vastness of the cavities on site, which could cause very large sinkholes should the cavity mobilise to surface. While 52 % of the holes had a grout take of more than 1 m^3, the holes that took more than 1 m^3 used 89 % of the total quantity of grout used on the project. While only 4 % of the grout holes took more than 10 m^3 of grout, the holes that took more than 10 m^3 took 47 % of the total amount of grout used on the project.

The grout takes were therefore very large in some holes, but the majority of the holes did not take significant amounts of grout. Most of the grout used on the project was pumped into holes with large grout takes, although the hole with big grout takes made up a small percentage of the total amount of grout holes on the project.

5 CONCLUSIONS

A dolomitic sinkhole that formed in the road reserve of a major highway in Gauteng caused multiple lanes to be closed for the safety of road users. A geotechnical investigation was done, and certain site-specific challenges were identified.

Based on this, the remediation design was tailored to suit the site conditions. The remediation design included blocking the sinkhole throat with grout bags, filling the sinkhole with low strength concrete and compaction grouting.

Challenges were encountered during the implementation phase of the contract but were overcome to successfully complete the remediation.

6 RECOMMENDATIONS

The following recommendations can be made:
1. The grout bag method is a viable method of remediation of dolomitic sinkholes.
2. When remediating dolomitic sinkholes, it is recommended that both the Engineer and Contractor are adaptable to site conditions and willing to work together to develop iterative methods to complete the remediation.
3. Drilling in poor dolomite conditions are very challenging, which can affect the timeframes of compaction grouting projects.
4. When grouting in dolomite, there are large variation in grout takes, making the prediction of quantities of grout required for remediation extremely challenging.

ACKNOWLEDGMENTS

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REFERENCES

Brink, A.B.A. & Bruin, R.M.H. 1990. Guidelines for soil and rock logging in South Africa. In 2nd Impression, Proceedings: Geoterminology Workshop.

Kleinhans, I. & Van Rooy, J.L. 2016. Guidelines for sinkhole and subsidence rehabilitation based on generic geological models of a dolomite environment on the East Rand, South Africa. *Journal of African Earth Sciences* 117: 86-101. https://doi.org/10.1016/j.jafrearsci.2016.01.001

SABS. 2012. *SANS 1936 Part 2: Geotechnical investigations and determinations*.

Zhou, W. & Lei, M. 2017. Conceptual site models for sinkhole formation and remediation. *Environmental Earth Sciences* 76(24). https://doi.org/10.1007/s12665-017-7129-0