Case study: Investigation vs construction for a sinkhole remediation project

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ABSTRACT: This paper compares the findings of an investigation with the subsequent conditions encountered during construction for two sinkholes that developed within the road reserve of a major highway located in Johannesburg. The investigation comprised of geophysical surveys followed by percussion drilling to develop an understanding of the underlying dolomitic conditions and associated risk of sinkhole and/or subsidence formation. Geophysical surveys were initially conducted to identify potential cavities, sinkholes and/or unstable areas present below the site. This was followed by percussion drilling to assess the underlying conditions present at depth and an assessment of the associated risk of sinkhole formation across the site. In some respects, the investigation accurately predicted the on-site conditions encountered during construction, thus proving to be an effective method for an assessment of risk. However, in other cases, discrepancies were found, which highlight the variability of dolomite formations over short distances and the associated challenges of risk characterisation that is limited to point data.

1 INTRODUCTION

A sinkhole remediation project has recently been completed for two sinkholes that developed within the road reserve of a major highway in Johannesburg. The project provides an opportunity to compare the findings of a comprehensive geotechnical investigation with the actual conditions encountered on site during construction, with the aim of evaluating the effectiveness of using point data to determine the risk associated with sinkhole/subsidence formation on a site.

Following a period of high intensity rainfall, a 13 m wide x 8 m deep sinkhole formed within the road reserve adjacent to the northbound carriageway of a 4-lane highway. Settlement type cracks were observed running parallel to the highway along the paved Lane 1 and Lane 2 (i.e. the two slow lanes) adjacent to the sinkhole. This resulted in Lane 1 and Lane 2 of the Northbound carriageway being closed as an interim precautionary measure. A secondary sinkhole (11 m wide x 5 m deep) situated at the toe of the road embankment was identified as part of the investigation, which could also directly affect the road embankment, and hence the roadway, should further instability occur. An additional eight sinkholes were identified directly west of the study area. However, these sinkholes were located outside the road reserve and study area. Aside from the challenge of being bounded by a major highway on the east and numerous sinkholes to the west, the site is also constrained by high voltage overhead powerlines. The positions of the sinkholes relative to the road is shown in Figure 1.

The investigation was aimed at assessing the extent of the sinkholes and providing sufficient information required to develop an effective remediation design.

The primary objective of the remediation design was to largely eliminate the risk of future sinkholes forming within the road reserve. In the unlikely event of a sinkhole formation beneath or adjacent to the highway, the design aims to limit the potential damage to the appearance of cracks and surface deformation, rather than an immediate and catastrophic failure of the highway.

2 METHODOLOGY

2.1 *Investigation*

The site is underlain by dolomite and dolomitic residuum of the Malmani Subgroup of the Chuniespoort group which forms part of the Transvaal Supergroup (According to the published 1:250 000 geological map, sheet 2528 Pretoria). This subgroup is one of three subgroups notorious for sinkhole and subsidence formation in South Africa (Kleinhans et al. 2016).

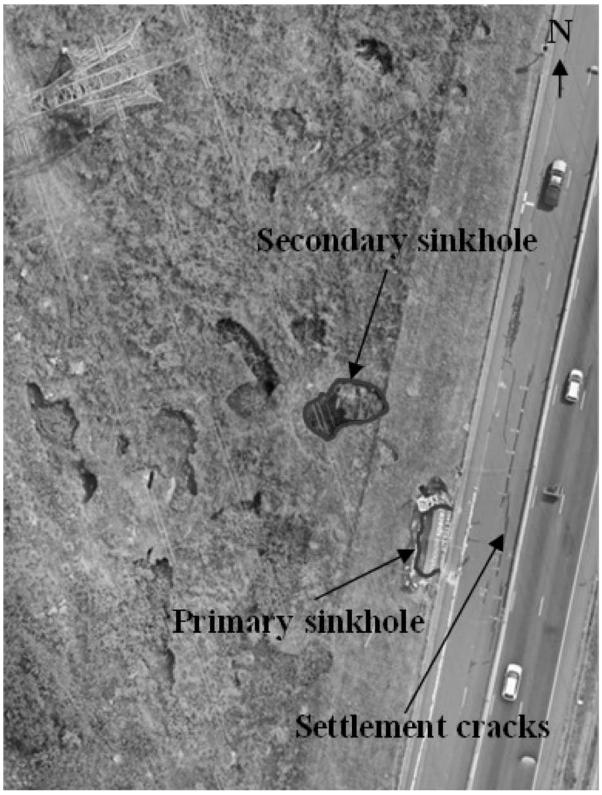

Figure 1. Site layout and location of the sinkholes

The geotechnical investigation comprised of an initial phase aimed at identifying the general risks or hazards associated with placing personnel and equipment in close proximity to the sinkholes, in order to develop a plan on how to execute the required works as safely as possible. This comprised a review of topographical and drone surveys as well as completing a comprehensive suite of geophysical surveys. The topographical and drone surveys assisted in determining the physical extent of the problem areas and positioning of the active sinkholes in the greater area. Geophysical surveys, comprising Ground Penetration Radar, Electrical Resistivity Tomography (ERT), Multichannel Analysis of Surface Waves (MASW) and gravity surveys, were used to interpret the extent of cavities or weakened areas along the roadway and road reserve. This included surveying the median and road reserve of the southbound carriageway.

In the second phase of the investigation, 71 percussion boreholes were drilled in selected areas across the site. The selection was based on site accessibility and zones exhibiting poor subsurface conditions and anomalies, as identified by the surveys. A specialist drilling contractor was appointed to drill the boreholes with a short mast percussion rig (i.e. 3.5 m high) to account for the low-lying overhead transmission and distribution lines present across the site. Selected boreholes located outside the powerline servitude were drilled with a conventional percussion rig.

The investigation was initially limited to the northbound carriageway, targeting the areas located in close proximity to the sinkholes. However, the initial stages of drilling confirmed very poor dolomitic conditions over a wider area, with very thick wad layers and very low penetration rates. The larger than expected extent of the high-risk dolomitic conditions became evident and it became clear that the unfavourable conditions extended beyond the northbound carriageway. This resulted in the extension of the investigation area further north and south on the northbound, as well as limited areas in the median, fast lane and road reserve of the southbound carriage way.

Additional boreholes were drilled whenever major differences in subsurface conditions were noted between adjacent boreholes, to better define the boundaries of the transitions and determine the extent of area requiring remediation. This approach places emphasis on the importance of not only focusing remediation at the affected area but extending into adjacent regions that are vulnerable to similar high-risk dolomite.

The boreholes were drilled to either a depth of 60 m, or until 6 m of competent dolomitic rock had been proven as per the requirements of SANS 1936. Chip samples were taken at 1 m intervals and logged on site according to the current standard procedures proposed by Brink & Bruin (2002). The site was zoned into different Inherent Hazard classes (IHC), in accordance with SANS 1936.

2.2 *Remediation Design*

The investigation provided critical information on the sinkhole triggers, subsurface conditions and risk / impact on infrastructure which were considered on a statistical, risk-based approach to develop an effective final remediation design.

Remediation comprising plugging the sinkhole throat with grout bags filled with a cement:soil grout mix followed by soilcrete coupled with compaction grouting was deemed to be the most practical and cost-effective solution for the rehabilitation of the sinkholes and the adjacent area respectively. Plugging of the sinkhole was initially carried out to stabilise the existing sinkholes and prevent further collapse of the sinkhole sidewalls and damage to the road reserve. Compaction grouting was, thereafter, carried out for rehabilitation of the entire 250 m long section of the highway affected by the sinkhole (s) characterised by poor dolomitic conditions. This included the northbound and southbound carriageways, its road reserves as well as the median.

Compaction grouting involves the pumping of a highly viscous grout down a pre-drilled borehole, at a specific pressure. The grout filled voids and cavities at depth while increasing the density of poor and potentially erodible subsurface soils. This increases the soil strength and stiffness. Compaction grouting boreholes were drilled to a depth of either 25 m or 7 m into continuous hard rock. The "up-stage" method was used – grouting from the bottom of a borehole and raising the casing tube in increments of 1 m when either a predetermined grout pressure was achieved, or a maximum volume of grout was pumped. The compaction grouting was carried out on a 5 m square grid, consisting of a series of Primary, Secondary and Tertiary points. Primary points were drilled first followed by secondary points lying midway to the primary point. In some instances, tertiary and post-tertiary points were added. The inclusion of tertiary holes was necessary where excessive grout takes occurred or due to extremely poor subsurface conditions observed by the on-site drilling team.

3 RESULTS

3.1 *Investigation findings*

Findings from the gravity survey is illustrated in Figure 2. A strong gravity gradient which can be indicative of karst dolomitic conditions occurs very close to the position of the primary sinkhole and trends in a southerly direction. An area with low gravity is evident in the southern part of the site which may suggest a regional gravity trend from low to high in a south to north direction. A zone of high gravity is located to the east of the sinkholes, which indicates the possibility of shallower dolomite bedrock, or a change in lithology. A low gravity feature is located towards the north of the site.

Interpretation of the ERT data suggested the location of possible cavities (shown in red blocks) and thick wad layers (shown in blue blocks) on the map. These features were identified in close proximity to the sinkholes as well as further south / southeast.

The general profile encountered during the drilling campaign comprised the following:

- Fill / transported soil to depths of between 1.0 m and 7.0 m below ground level.
- Highly weathered chert varying from 1.0 m to 28 m thick.
- Interbedded chert and wad in 60 % of boreholes. Thickness varied from 1.0 m to 50.0 m.
- Wad in 50 % of boreholes with an average thickness of between 1.0 m and 40.0 m.
- Depth to dolomite bedrock generally varied from 15.0 m to 45.0 m, with shallower bedrock evident in the northern portion of the northbound carriageway.

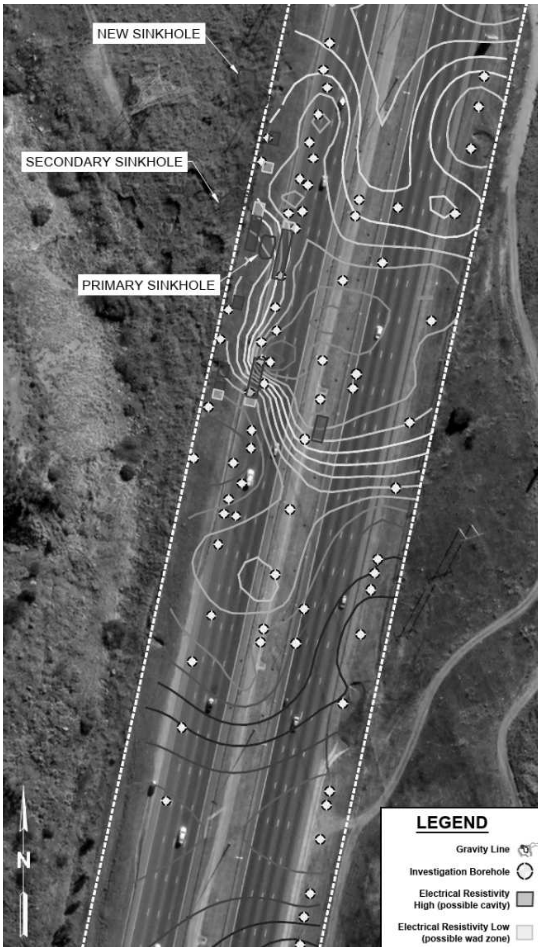

Figure 2. Gravity survey and ERT zones of interest.

Very low penetration rates (less than 0.05 min.s/m), cavities and sample loss were evident throughout the site. Following completion of the drilling campaign, the site was subdivided into three major zones, as illustrated in Figure 3 and described below:

- Zone A: IHC 3 and 4 (Overall risk to the road = Low)
  Boreholes drilled within this zone were designated to be underlain predominantly by Inherent Hazard Class 3 and 4 conditions. Within this zone, there is a medium susceptibility for the development of small (i.e. < 2 m diameter) and medium (i.e. 2 m to 5 m diameter) sized sinkholes and a low to medium susceptibility for the development of large sinkholes (i.e. 5 m to 15 m). There is also a medium susceptibility for the development of dolomite related subsidence.
- Zone B – IHC 6 (Overall risk to the road = Moderate)
  Within this zone, the boreholes were predominately classified as having a high susceptibility for the development of small and medium sinkholes (i.e. 2 m to 5 m diameter) and subsidence development and low susceptibility for the development of large and very large (i.e. 5 m to > 15 m diameter) sinkholes.

- Zone C – IHC 7 and IHC 8 (Overall risk to the road = high to very high)
  Based on the boreholes drilled, this zone is characterised as having a high susceptibility for the development of small, medium and large sinkholes (i.e. 2 m to 15 m diameter) and subsidence development. IHC 7 conditions are considered to have a low susceptibility for the development of very large sinkholes. However, IHC 8 indicates that there is a high susceptibility for the development of very large sinkholes (i.e. > 15 m diameter).

A sequence of boreholes drilled to the north of the sinkholes, including targeting areas of interest identified from the ERT survey, consistently encountered shallow bedrock which contributed to a IHC 3/4 classification. Isolated pockets of IHC 3 and IHC 4 conditions were noted within Zone C, which was interpreted as isolated boreholes encountering pinnacles present across these portions of the site.

Zone C was designated as high to very high risk, particularly given the high chance of very large sinkholes forming. This area was therefore identified as the area requiring remediation.

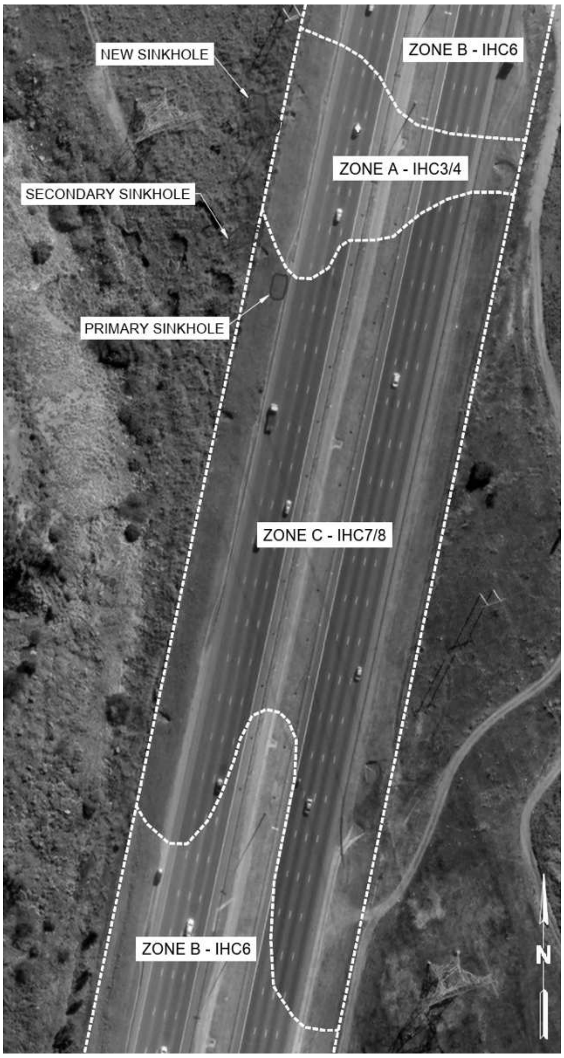

Figure 3. Dolomite Inherent Hazard Classification for the site.

3.2 *Construction Phase findings*

The investigation phase provided the necessary insight into the extent of remedial work required. The design of the compaction grouting comprised of a borehole grid pattern that spanned beyond the northern and southern boundaries of Zone C (i.e. characterised by IHC 7 and IHC 8 conditions), with a total of 1400 boreholes to be drilled. The budget included an allowance for 201 tertiary holes to be included at to-be-identified locations, based on grout quantity used as well as subsurface conditions seen by the on-site team during construction.

Following a period of heavy rainfall during construction phase, a new sinkhole formed adjacent to the northbound road reserve. This was in close proximity to an area previously characterised as Zone A (IHC 3/4) located to the north of the sinkholes and was, therefore, not included within the original remediation area extent. The development of the sinkhole highlights the gaps that can manifest when relying on point data to assess a site, regardless of how comprehensive this investigation may seem.

The development of this sinkhole required an extension of the remediation area by an additional 30 m to the north for phases 1 and 2 to ensure the safety and stability of the highway should the new sinkhole expand further, as shown in Figure 44. The inherent variability of dolomite, combined with external factors like heavy rainfall, means that subsurface conditions can evolve in ways that are difficult to anticipate. This occurrence highlights the importance of remaining adaptable within the design and construction phases, to the variability and unpredictability of dolomite conditions, even in areas initially deemed lower risk.

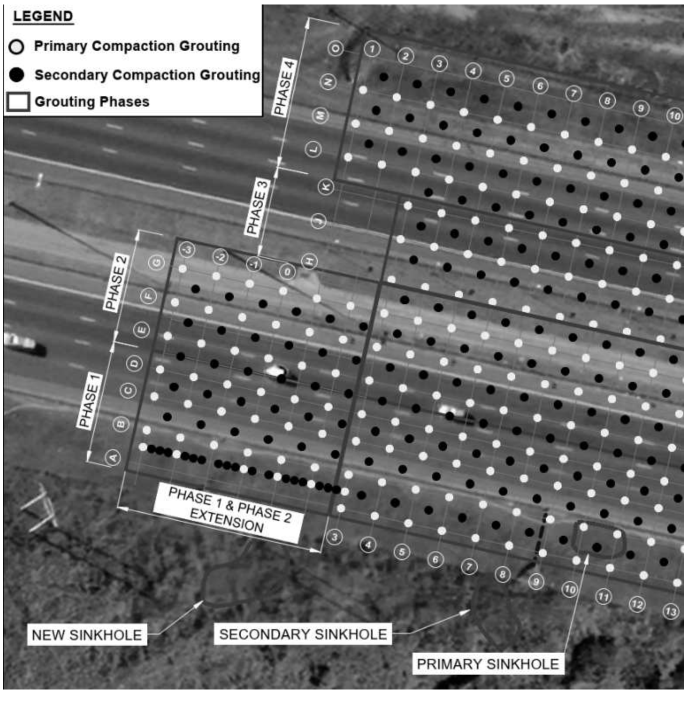

Figure 4. Remediation area extension due to sinkhole I formation.

The final remediation phase resulted in a total of 1747 boreholes drilled – 347 boreholes more than anticipated. Figure 5 shows all boreholes drilled during the construction phase overlaid on the bouger gravity survey. Steep gravity gradients and low gravity trends are generally considered to be areas of concern during a dolomite investigation. These features are representative of steeply sloping bedrock and highly weathered subsurface conditions, and thus considered high risk areas (Wagener 1985). The black clusters of boreholes on the figure reflect areas where tertiary and/or post-tertiary boreholes were required. Concentration of boreholes is an indication of exceptionally poor subsurface conditions. This may be due to the presence of void or cavities within a profile, or zones of highly weathered, low density features which are highly prone to erosion thus significantly increase the risk of sinkhole formation.

Figure 5 and 6 show a good correlation between areas of concern identified by the bouger survey and clusters of boreholes drilled during construction. Dense concentration of boreholes reflect locations where secondary and tertiary boreholes were added, in response to high grout takes or challenging subsurface conditions encountered on site. These borehole clusters were concentrated on regions of high gravity gradient and low gravity trends, aligning well with the survey's findings. However, some outliers were observed where the survey did not detect localised areas of exceptionally poor subsurface condition (as depicted by the concentration of boreholes).

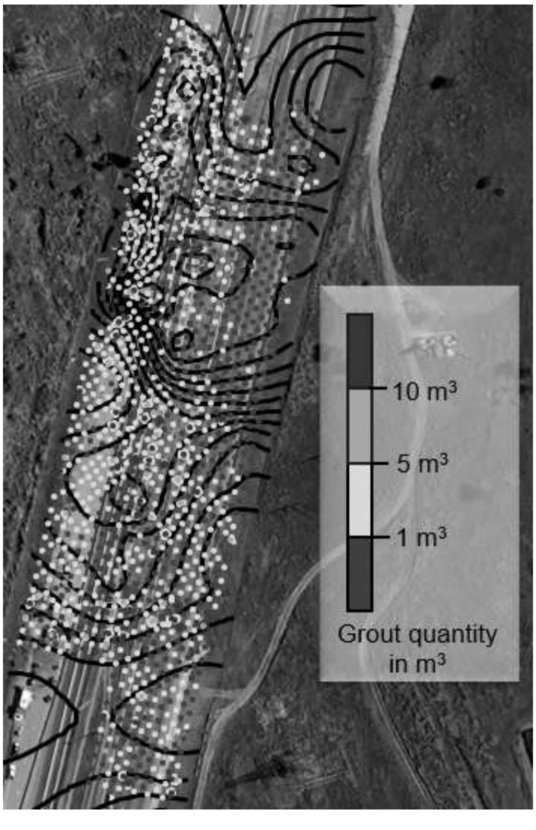

Figure 5. Grout takes in m^3 for each borehole.

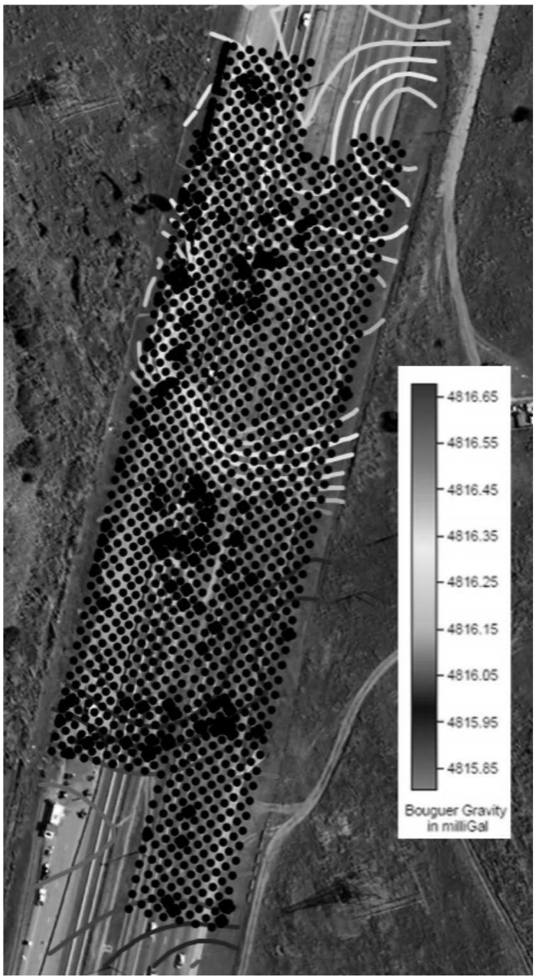

Figure 6. Comparison between the gravity survey and boreholes drilled during compaction grouting

Figure 7 illustrates the distribution of boreholes that terminated on bedrock within the upper 25 m of the profile, overlain on the gravity survey map. The higher gravity regions, coloured in red, are indicative of shallow bedrock while the lower gravity portions, coloured in blue, are indicative of deeper lying bedrock. The figure reveals a notable concentration of boreholes terminated in bedrock within areas of high gravity, which aligns well with expectations. This consistency between the gravity survey and actual onsite conditions provides validation of the gravity survey's reliability as a tool for identifying depths to bedrock.

However, there are boreholes within the low gravity area that also reached bedrock. This suggests the occurrence of localised variations within the regions characterised by deeper lying bedrock, which were overlooked by the survey. While this discrepancy is considered to be insignificant in terms of the efficacy of the design, it does highlight the complexity of predicting subsurface dolomitic conditions, even with advanced geophysical techniques. However, the overall reliability of the survey is well-supported by the broader consistency of the findings.

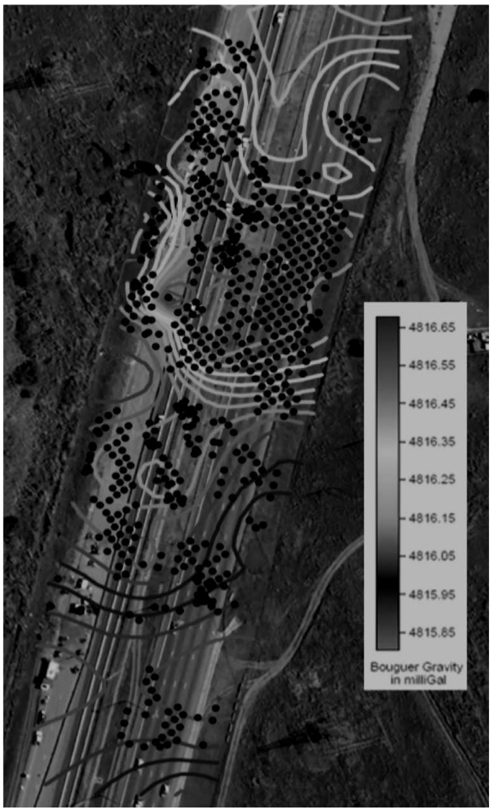

Figure 7. Comparison of boreholes reaching bedrock (< 25 m) and gravity survey results.

4 CONCLUSIONS

Throughout this project, a theme that emerged constantly was the inherent unpredictability of dolomite formations, which makes it more challenging to accurately predict subsurface conditions. The overall reliability of the surveys was well-supported by the broader consistency of the findings, with poor subsurface conditions being noted in areas of concern identified by the survey. While surveys are invaluable tools, they cannot guarantee perfect accuracy in every case. These tools may overlook localised anomalies. Utilising a combination of tools is required to improve confidence in the data obtained.

However, the tools available serve as a vital foundation in providing an understanding of subsurface conditions, which allow for appropriate, informed decisions to be made. Subsurface conditions can rapidly evolve in ways that are difficult to anticipate, as seen with the development of an additional sinkhole in close proximity to an area deemed to be of lower risk. This highlights the need to be adaptable when working with dolomite and the critical need to remain open to extending investigations and adjusting scopes of works as new risks and challenges arise. Limiting an investigation prematurely can lead to incomplete data, inadequate solutions, and ultimately higher costs and risks. One must accept and embrace unpredictability as an inherent part of the process of working on dolomites, and design accordingly.

5 RECOMMENDATIONS

The following recommendations are considered applicable:

- Geophysical tools such as gravity and ERT surveys remain a useful tool for scoping and planning geotechnical investigations.
- Utilising a number of different tools and methods is recommended to improve confidence in the data obtained.
- The drilling of percussion boreholes to investigate features that have been identified in geophysical surveys can be unreliable due to the inherent variability of dolomite land over short distances.
- The use of point data may be unreliable when assessing the risk of sinkhole formation.

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REFERENCESS

Brink, A.B.A & Bruin, R.M.H. 2001. Guidelines for Soil and Rock Logging in South Africa, 2nd Impression 2001, eds. A.B.A. Brink and R.M.H. Bruin, Proceedings, Geoterminology Workshop organised by AEG, SAICE and SAIEG, 1990.

Buttrick, D.B., Van Schalkwyk, A., Kleywecht, R.J. & Watermeyer, R.B. 2001. Proposed method for dolomite land hazard and risk assessment in Southern Africa. *Journal of the South African Institution of Civil Engineering* 43(2): 27-36.

Buttrick, D.B.1995. The Method of Scenario Supposition for Stability Evaluations of sites on dolomitic land in South Africa. *SAICE Journal* Fourth Quarter 1995.

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.

SANS 1936-1. 2012. Development of dolomite land – Part 1: General principles and requirements.

SANS 1936-2. 2012. Development of dolomite land – Part 2: Geotechnical investigations and determinations.

SANS 2001-BE3. 2012. Repair of sinkholes and subsidences in dolomite land.

Wagener, F. 1985. Problems of soils in South Africa: Dolomites. *The Civil Engineer in South Africa* July 1985: 395-407.

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