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Guidelines for sinkhole and subsidence rehabilitation based on generic geological models of a dolomite environment on the East Rand, South Africa

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A R T I C L E I N F O

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A B S T R A C T

A sound understanding of the various factors influencing and associated with the formation of sinkholes or subsidences on dolomite land is essential for the selection of appropriate rehabilitation methods. The investigation and rehabilitation of numerous sinkholes and subsidences located on dolomite in the East Rand of South Africa, created an opportunity to develop a broad based understanding of different karst environments, their susceptibility to sinkhole and subsidence formation and best practice rehabilitation methods. This paper is based on the guidelines developed whereby the geological model of the sinkhole or subsidence is used to recommend an appropriate rehabilitation method. Nine typical geological models with recommended rehabilitation methods are presented in this paper.

1. Introduction

Engineering problems related to karst features, including sinkholes and subsidences, on carbonate (limestone and dolomite) and evaporite (gypsum and salt) rocks is common all over the world, including the United States of America, United Kingdom, Europe, Asia and Africa and have been documented by various authors (Buttrick et al., 2001, 2011; Waltham et al., 2005; Ford and Williams, 2007; Zhou and Beck, 2011; Galve et al., 2012; Gutierrez et al., 2014 and Parise et al., 2015).

A sinkhole is defined as a feature that occurs suddenly and manifests as a hole in the ground that is typically circular in plan. In international literature the term sinkhole is often synonymous with doline (SANS, 1936, 2012). A subsidence is defined as a shallow enclosed depression that occurs slowly over time and may typically be circular, oval or linear in plan (SANS, 1936, 2012).

The formation of sinkholes have negative social and financial implications in the affected and immediately surrounding areas, resulting in the relocation of entire communities to safer ground, severe damage to infrastructure or even loss of human life (Waltham et al., 2005; Buttrick et al., 2011). On the Far West Rand of South Africa, sinkholes induced by the dewatering of dolomite groundwater compartments for gold mining caused the loss of life of 38 people (De Bruyn and Bell, 2001). A community of approximately 30 000 households was relocated to safer ground in a dolomite area west of Johannesburg, South Africa, at a cost exceeding US $600 million (Buttrick et al., 2011). In Calatayud (Spain), underlain by evaporites, and Allentown (Pennsylvania, USA), underlain by cavernous limestone, sinkhole events have caused the demolition of multi-storey buildings with direct economic losses in excess of US $6.3 million and US $8 million, respectively (Dougherty, 2005; Gutierrez et al., 2008). Parise and Lollino (2011) reports on the impact of natural and man-made limestone caves on infrastructure in the Apulia region, southern Italy. The impact of subsidences in the city of Tuzla (Bosnia and Hertzegovina) related to the extraction of salt deposits by solution mining is reported by Mancini et al. (2009). Guerrero et al. (2008) present a review on detrimental effects caused by sinkholes on railways and Galve et al. (2012) and Villard et al. (2000) reports on the impact of sinkholes on roads in Spain and France.

It is essential that the various influencing factors associated with

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the formation of sinkholes and subsidences on carbonate bedrock are understood to allow for the selection of appropriate rehabilitation methods. The main objectives when investigating sinkholes and subsidences are to determine the cause as well as the extent of subsurface erosion, the impact on existing infrastructure and the appropriate rehabilitation methodology to improve subsurface conditions, prevent further instability and render the area safe for future development.

The specific method of investigation and subsequent rehabilitation actions are usually determined by the accessibility of a site. Accessibility constraints within a built-up area, including existing infrastructure, may lead to investigation and rehabilitation methods that differ from those generally preferred in unrestricted areas. The goal is to obtain as much subsurface information as possible to develop a 3-Dimensional model of the subsurface conditions that need improvement.

Karst terrain susceptibility and hazard mapping is one of the mitigating measures that has evolved in countries such as the USA, England, Spain, Italy, Belgium and South Africa (Waltham et al., 2005; Gutierrez et al., 2014). The most important step in sinkhole hazard analysis, once the sinkholes and areas affected have been mapped and characterised by means of surface and subsurface investigation methods, is the construction of a comprehensive cartographic sinkhole inventory (Gutierrez et al., 2014). Sinkhole databases should include information on: precise location of the limits of the sinkholes and underlying subsidence structures, morphometric parameters, genetic type (sinkhole or subsidence mechanisms and material affected), chronology, activity and relationship with conditioning and triggering factors (Gutierrez et al., 2014).

Parise and Lollino (2011) and Parise (2015) for example, developed numerical analyses for the implementation of 2- and 3-Dimensional stability models using the finite element method for geological settings represented by continuous soft rock mass, and the distinct element method for jointed rock masses (highly stratified limestone) to evaluate the susceptibility to sinkhole development related to cave systems, anthropogenic features (underground quarries) and natural occurrences, in southern Italy.

Instability features are largely anthropogenic (i.e. caused by human activities) and have a detrimental impact on infrastructure with potential for loss of life. Hence poor maintenance of wet services, poor management of surface water run-off, poorly backfilled service trenches, lack of monitoring and control of the original groundwater level in the dolomite profile and ground vibrations (e.g. heavy machinery, passing trains or blasting) have the potential to trigger events (Buttrick and Van Schalkwyk, 1998). Natural and human-induced static and dynamic loadings e,g, load imposed by heavy vehicles, drilling rigs, dumped material and engineered structures, may trigger the collapse of pre-existing cavities under marginal conditions, (Gutierrez et al., 2014). These conditions may cause the mobilization of the overlying in situ materials into voids located within or above bedrock, leading to the formation of sinkholes or subsidences and damage to infrastructure (Kleinhans and Van Rooy, 2014).

The rehabilitation of sinkholes and subsidences is affected by a number of aspects, such as available funding, existing and future land use, geological factors and the depth to the groundwater level (Kleinhans and Van Rooy, 2014).

In South Africa, the investigation and rehabilitation of these features prior to the 1970's were undertaken by trial and error as there were no guidelines. The assessment of surface stability on dolomite land was formulated by Buttrick (1992) and Buttrick et al. (2001, 2011) with the development of the so-called “Method of Scenario Supposition”.

The investigation and rehabilitation of numerous sinkholes and subsidences on dolomite bedrock occurring in the East Rand of the Gauteng Province, South Africa, made it possible to develop an understanding of the different dolomite karst environments, their susceptibility to sinkhole and subsidence development and best practice rehabilitation methods. Generic geological models and most appropriate rehabilitation methods were developed to serve as a guideline for sinkhole and subsidence rehabilitation that may also be applicable in other carbonate rock regions affected by sinkholes and subsidences. The East Rand covers the eastern part of the Gauteng Province in South Africa and approximately 50% of the area is underlain by dolomite bedrock within 60 m from ground surface, also referred to as “dolomite land” (SANS, 1936, 2012).

In the Gauteng Province, the dolomite of the Malmani Subgroup, Chuniespoort Group, Transvaal Supergroup is notorious for sinkhole and subsidence formation and is subdivided into the Oaktree, Monte Christo, Lyttleton and Eccles Formations, which are differentiated based on their chert content, stromatolite morphology, intercalated shales and erosion surfaces (Buttrick and Van Schalkwyk, 1998). The Monte Christo and Eccles Formations are generally rich in chert and the Oaktree and Lyttleton Formations contain chert-poor dolomite (Buttrick and Van Schalkwyk, 1998). According to Button (1973) and Eriksson and Truswell (1974), the dolomite rocks of the Malmani Subgroup are approximately 2200–2300 Ma years old.

2. Evaluation of sinkholes and subsidences to determine rehabilitation method

A number of factors need to be established after the occurrence of a surface instability event to be able to develop the geological model. One of the most important factors influencing the rehabilitation approach is the depth below surface to which rehabilitation is required.

2.1. Depth of impact

For rehabilitation purposes sinkholes or subsidences can be evaluated according to the same influencing factors grouped under a specific depth of impact:

- Shallow depth: Impact extending to a maximum depth of 8 m.
- Intermediate depth: Impact extending to a maximum depth of 15 m.
- Great depth: Impact extending to a depth of more than 15 m.

The depth of impact refers to the depth to which the subsurface profile is anticipated to have been influenced during the development of a sinkhole or subsidence. For a shallow depth of impact (maximum 8 m), the throat of the sinkhole or lower limit of subsidence is reachable by an excavator if all other influencing factors allow the use of such large and heavy equipment. For an intermediate depth of impact (maximum 15 m), various rehabilitation procedures or a combination of procedures may be considered and will depend on the geological model and external influencing factors such as accessibility for rehabilitation equipment and the impact on existing infrastructure. For a great depth of impact (more than 15 m), the base of the sinkhole can only be reached by means of drilling.

Zhou and Beck (2008) divide sinkholes into shallow and deep sinkholes for mitigation purposes. Shallow sinkholes are, according to them, those that are no more than 10 m deep, and their bases are reached by a regular backhoe. Deep sinkholes are more than 10 m deep, and drilling rigs are needed to reach their bases (Zhou and Beck, 2008).

2.2. Factors determining rehabilitation method

For each of the aforementioned depths of impact, the following influencing factors are taken into consideration to determine the most appropriate rehabilitation method or combination of methods.

2.2.1. Cause of sinkhole or subsidence formation

Sinkhole or subsidence formation in South African karst is typically evaluated from an ingress of water and groundwater level drawdown perspective (Buttrick et al., 2001, 2011).

- *Ingress of water*: The infiltration of water is the most common cause of sinkhole or subsidence formation in urban areas and is mostly related to leaking or broken wet services.
- *Groundwater level drawdown*: Dewatering of dolomite groundwater compartments is associated with the over-utilisation of groundwater for agricultural purposes or dewatering related to mining activities.

The mechanism of sinkhole and subsidence formation from an ingress of water and groundwater level drawdown perspective is described in detail by Jennings et al. (1965) and Brink (1979).

2.2.2. Complexity of the geological model

Over geological time, dolomite rock is dissolved and removed as bicarbonates of calcium and magnesium by weakly acidic rainwater and percolating groundwater (Buttrick and Van Schalkwyk, 1998). This process is facilitated by fault, fracture and joint networks and results in typical karst features, including interconnected cavities within the dolomite bedrock and a very irregular bedrock surface (Buttrick and Van Schalkwyk, 1998). Younger sediments, intrusives or residual materials (weathering products of dolomite and chert) commonly cover the karst landscape in South Africa and these materials are referred to as the dolomitic overburden or blanketing layer (Buttrick et al., 2011). Hard, fresh dolomite rock is overlain by slightly weathered jointed bedrock (epikarst) with a sudden transition to totally weathered and low-strength, insoluble residual material consisting mainly of a low density, fine grained, black to blue–grey clayey silt or silty clay rich in silica and manganese oxides (referred to as "wad" in South African nomenclature), chert or a mixture of wad and chert rubble (collapsed remnants of the chert interbeds) and iron oxides that reflect the original insoluble matrix structure (Buttrick and Van Schalkwyk, 1998). Residual dolomitic soils are commonly very porous, erodible and compressible. These properties are due to leaching and gap grading between wad and chert rubble (Buttrick and Van Schalkwyk, 1998). Due to natural compaction and ferruginization near the ground surface, dolomite profiles are typically characterised by poorer geotechnical characteristics with depth (Buttrick and Van Schalkwyk, 1998) where the uppermost part of the soil horizon is often of higher density and strength and relatively impervious compared to the deeper horizons.

The simplicity or complexity of the geological model depends on the following:

- Blanketing layer:
  - *Composition and thickness of the blanketing layer*: The mobilization potential increases where low density material (dolomite residuum) and especially thick horizons of dolomite residuum (wad) are present in the profile, and voids (or disseminated receptacles) that may be able to accommodate mobilized material from overlying horizons are present.
  - *Presence of vertical or sub-vertical intrusives or shale directly in contact with dolomite residuum (wad or ferroan soils)*: Typically intrusive or shale is regarded as material with a low mobilization potential adding stability to the blanketing layer. However, the contact zone between these materials of low mobilization potential and the dolomite residuum may in areas act as a contributing factor to the formation of a sinkhole or a subsidence. These contact zones may act as preferential pathways for mobilized material into voids or cavities at depth.
  - *Presence of faults or fracture zones*: Depending on the nature of the faults or fracture zones present, these may act as preferential pathways or conduits to voids below.
  - *Roof capping material over a void or cavity*: The geological profile is regarded as complex from a rehabilitation perspective where dolomite residuum (wad) is overlain by a horizon of competent chert, with subsurface erosion having taken place within the dolomite residuum (wad) creating a void or disseminated voids (receptacles) below the competent chert horizon.
  - *Geotechnical characteristics of material in the blanketing layer*: The grading, density and permeability of horizons in the blanketing layer also play a vital role, as soil types comprising silty and clayey material with a low permeability will have a higher resistance to subsurface erosion, whilst sandy and gravelly soils with a high permeability and typical low density may be more susceptible to subsurface erosion.
  - *Presence of a paleo instability feature*: A paleo-sinkhole or subsidence may present an area of high susceptibility for reactivation.
- Dolomite bedrock depth and morphology:
  - The depth to dolomite bedrock influences the maximum potential size (diameters and depth). Small to medium size sinkholes or all size subsidences are typically associated with dolomite bedrock at shallow to intermediate depths (<15 m) and medium to very large size sinkholes or subsidences are associated with deep dolomite bedrock (>15 m).
  - The karst landscape associated with the weathering processes of dolomite can create variable bedrock morphologies, ranging from simple to very complex, depending on the stage of karst development (i.e. juvenile, youthful, mature, complex or extreme (Waltham and Fookes, 2003)) and the presence of faults, fractures and intrusions.
    - A simple geological model is typically associated with juvenile karst (Waltham and Fookes, 2003) where the dolomite bedrock is gently undulating to nearly horizontal, with a homogeneous overlying blanketing layer.
    - A very complex geological model, according to Brink (1979), comprises of pinnacled dolomite bedrock at variable depths over a short lateral distance, the presence of geological structures and a heterogeneous blanketing layer typically comprising of dolomite residuum (wad), grykes (deeply weathered joint or 'solution enlarged joint') typically filled with dolomite residuum (wad) and voids, solution cavities within dolomite bedrock and remnants of the original dolomite bedrock present as floaters in the blanketing layer.
- Depth or position of the groundwater level in the dolomite profile:
  - The depth or position of the groundwater level in the dolomite profile, especially in the blanketing layer, plays a significant role in determining the susceptibility of the blanketing material to subsurface erosion into voids or cavities to create a sinkhole.
  - A subsidence may also develop if the downward migration of water through the dolomite residuum causes a densification (compaction) of the low density dolomite residuum.

- If the groundwater level is located above material with a high mobilization potential, a sinkhole or a subsidence will not occur, but sudden drawdown of the groundwater may expose low density materials or voids and deeper lying cavities within bedrock that may lead to the development of a sinkhole or subsidence.

The data needed for the compilation of the 3D geological model is generally gathered from geophysical surveys, specifically gravity surveys, followed by drilling of percussion boreholes, placed on gravity anomalies. The geophysical surveys are useful to indicate possible subsurface structures (e.g. cavities, voids, dykes, faults or geological contacts). In the South African karst environment the gravity method is regarded as the most successful geophysical method to determine dolomite bedrock topography and the thickness and density of overburden material (Kleywegt and Pike, 1982). The drilling of rotary percussion boreholes is regarded as one of the most reliable methods to obtain point data when assessing the extent of subsurface erosion related to sinkholes and subsidences, depth to dolomite bedrock, composition of the blanketing layer and the depth to the groundwater level (Brink, 1979). At sites with restricted access the Dynamic Probe Super Heavy (DPSH) Test Method can be used to determine the consistencies of the various soil horizons and to determine if cavities or shallow bedrock are present. In a shallow dolomite environment (bedrock within 8 m) an excavator can be used to expose subsurface conditions. On limestones in the United States and in Europe geophysical methods including Ground Penetration Radar (GPR), Electrical Resistivity (ER) and Seismic Refraction (SR) tests are commonly used to map the rock surface, determine subsurface characteristics and locate subsurface cavities (Kannan, 1997, Gutierrez et al., 2014). Due to the particular composition of the overburden on South African karst these geophysical methods are not very successful in delineating voids in the overburden or cavities within bedrock.

2.2.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

2.2.3.1. Depth and extent of instability feature. The manifestation of a sinkhole or subsidence at ground surface does not always define the depth and lateral extent of instability. The receptacle at depth, that accommodated the eroded material, may not be directly below the area of visual impact on surface, but can be located at distances more than 20 m from the sinkhole or subsidence. The evaluation of an event should therefore consider covering a surface area of between 20 m and 50 m around the sinkhole or subsidence area to ensure the instability feature has been thoroughly investigated.

2.2.3.2. Depth and extent of triggering mechanism (ingress of water). The first priority when dealing with a sinkhole or subsidence is to reduce or remove the cause or triggering mechanism and to reduce the likelihood of aggravating the problem (i.e. increase in sinkhole or subsidence size). In a built-up environment the triggering mechanism is typically related to ingress of water (e.g. leaking subsurface wet services or surface water ponding). The position of the point of ingress in the profile in relation to the instability feature may give a preliminary indication of the extent of the affected area to be investigated as well as the origin of the sinkhole or subsidence.

All affected wet services need to be replaced during the sinkhole or subsidence rehabilitation process. It is therefore critical that the depth and extent of the affected subsurface wet service and subsurface erosion is known prior to commencement of rehabilitation.

2.2.3.3. Impact on existing infrastructure. The position of the sinkhole or subsidence and damaged subsurface wet service in relation to the position of existing infrastructure plays a vital role in the rehabilitation procedures to be followed.

Infrastructure such as buildings, roads, overhead cables, subsurface services (for example gas pipes, water mains, electrical cables) that cannot be demolished, shut down or rerouted during the rehabilitation process need to be considered when the rehabilitation methodology is decided upon.

Existing infrastructure can sometimes prevent a detailed investigation of the sinkhole or subsidence due to access constraints and can lead to the area of impact being inadequately or incorrectly determined. This may lead to follow-up phases of rehabilitation of instability features such as erosion tunnels, cavities and voids discovered during the rehabilitation process.Where it is economically feasible, structures should be demolished, the area properly investigated, rehabilitated and only strategic structures then rebuilt, with appropriate precautionary measures.

Existing infrastructure may also limit investigation and rehabilitation of the instability feature and subsurface extent which may lead to an incomplete geological model and inappropriate rehabilitation.

2.2.4. Proposed land use after rehabilitation

The proposed land use post-rehabilitation also influence the choice of rehabilitation method. Usually the same land use is required after rehabilitation but in areas where the cost implications are excessive and a potential for re-occurrence exists, consideration should be given to the sterilization of the land. In areas where infrastructure has been affected by a sinkhole or subsidence, demolition and rebuilding are critical and the rehabilitation must produce subsurface conditions suitable for the specific land-use.

3. Sinkhole and subsidence rehabilitation methods

The Department of Public Works document PW344 (2010) lists various methods of sinkhole and subsidence rehabilitation used in South Africa and these methods are also incorporated in the South African National Standard on sinkhole rehabilitation (SANS, 2001-BE3, 2012).

The specific method, or combination of methods, used to rehabilitate sinkholes or subsidences depends on: a) the land-use after rehabilitation, b) available funding, c) the subsurface conditions (or geological model), d) accessibility for rehabilitation equipment and e) the impact of the rehabilitation procedure on existing infrastructure (Zhou and Beck, 2008; Kleinhans, 2013).

The objectives of sinkhole or subsidence rehabilitation are to:

- Expose and choke the throat of a sinkhole, remove highly compressible and erodible dolomite residuum (wad) and replace with competent materials creating an engineered earth mattress; OR
- compact subsurface materials by the drop of a large weight; OR
- backfill cavities at depth with an appropriate grout mixture.

Typical rehabilitation methods are described below:

3.1. Inverted filter method

The Inverted Filter Method comprises the backfilling of a sinkhole including blocking of the throat of the sinkhole with rockfill and/or boulders in combination with soilcrete (sandy gravel – G6 or G7 according to COLTO (1998) - with 3%–5% cement and water) or the use of self-compacting concrete. The blocking of the throat is followed by layers of progressively finer material ranging from cobble to sand size, compacted at a specific compaction effort to create an impermeable capping. Some of the finer layers are sometimes also stabilized with 3%–5% cement. A schematic presentation of the Inverted Filter Method is illustrated in Fig. 1.

Excavation and throat plugging is according to Zhou and Beck (2008) the simplest way to remediate an existing sinkhole. They suggest a plug of rock or stones, concrete blocks or grout of 1.5 times the width of the throat. If the sinkhole does not have an obvious throat, but consists of many discrete fractures, these fractures can be blocked by dental infill grout, where the pockets are filled with high/low slump flowable fill to plug and cap the fractures (Zhou and Beck, 2008).

The Inverted Filter Method is typically applied to:

- Sinkholes of small (<2 m diameter) or medium-size (2 m − 5 m diameter).
- Subsidences off all sizes (<2 m − > 15 m diameter).
- Sinkholes or subsidences with depths <8 m (or throat of sinkhole is visible within 8 m from natural ground surface).
- Events where existing infrastructure is located at a distance, outside the area proposed for bulk excavation.
- Shallow sinkholes within 10 m from natural ground surface (Zhou and Beck, 2008).

Geotextiles (geosynthetic reinforcement or geogrids) or mesh reinforcement (geogrids or weldmesh) are sometimes used to retain the material above the throat of the sinkhole or as support layers within the lower and top selected fill layers or to line the base and walls of the sinkhole (Zhou and Beck, 2008). It should however be noted that the use of geotextiles do not constitute a complete repair of a new or existing sinkhole (Villard et al., 2000). A geogrid can only serve as a temporary warning mechanism (Waltham et al., 2005). Geogrids may be used beneficially to improve load distribution on softer overburden material left in place on shallow

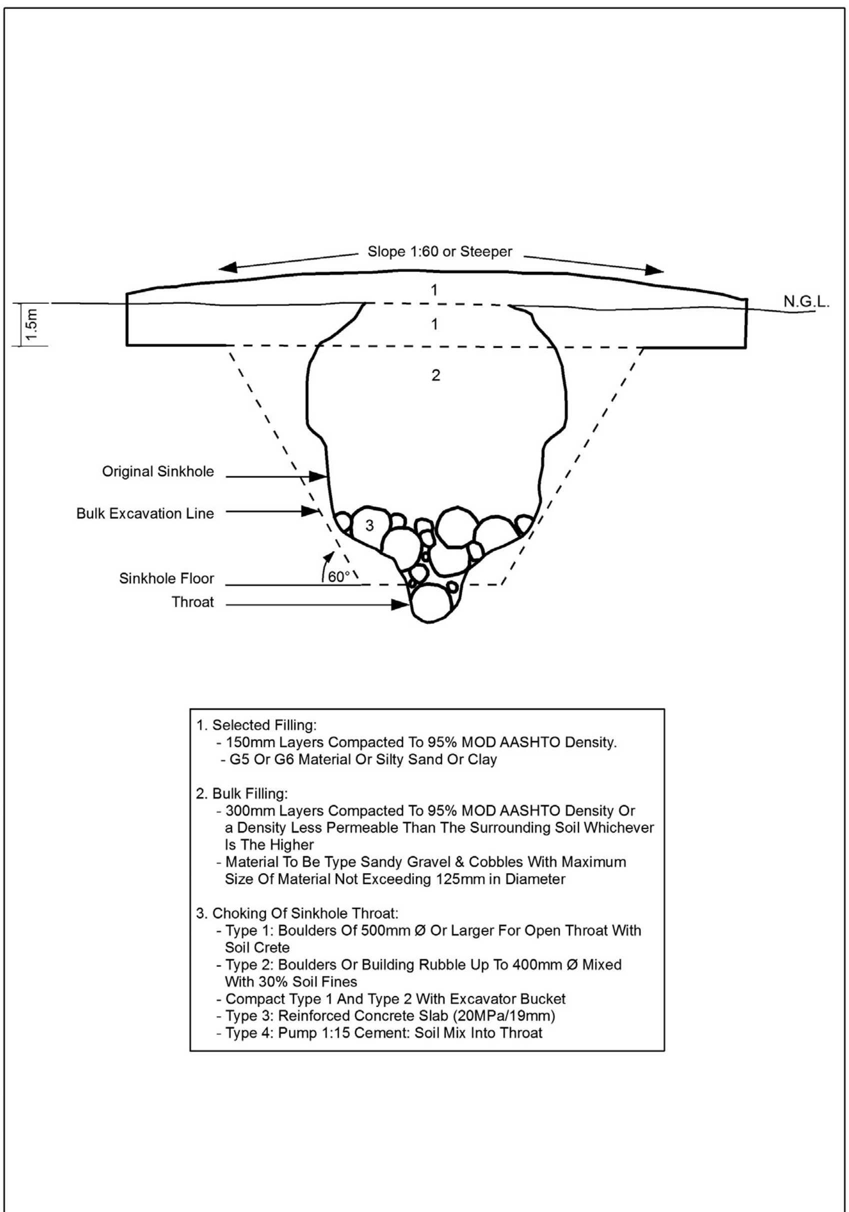

Fig. 1. Schematic depiction of the Inverted Filter Method used to rehabilitate a sinkhole (modified after PW344, 2010).

overburden strata (Zhou and Beck, 2008). Geosynthetics are generally cheaper than other measures (e.g. reinforced concrete slabs) when used as a prevention measure in roads and railways in areas prone to sinkhole formation, they are able to span small cavities, maintaining the serviceability of the road during the lifetime of the project and for large cavities they temporarily prevent the formation of catastrophic sinkholes and accidents, serving as a warning system (Galve et al., 2012). Galve et al. (2012) and Gutierrez et al. (2014) report on the development and evaluation of sinkhole susceptibility models to optimize the application of geosynthetics to roads. The most cost-effective geosynthetic design solution identified by means of the cost-benefit analyses involves the installation of geogrids able to span cavities 3 m–4 m in diameter distributed along 55% of the high risk road sections (Galve et al., 2012).

3.2. Dynamic compaction method (DC)

The DC Method involves placing of selected backfill materials typically in lifts of 2 m (can vary between 1 and 3 m), followed by dropping a large weight from a considerable height onto the material to be compacted (PW344, 2010). This is done on a set grid, including primary and secondary points carried out for each lift (or layer). The grid spacing for the primary DC-points for each layer varies typically between 5 × 5 m or 7.5 × 7.5 m and secondary DC points are positioned midway between the primary DC points. Compaction of the deepest layer is achieved with the primary phase and compaction of the intermediate layers by the secondary phases (Byrne et al., 1995). The final ironing compaction phase of the upper 2–4 m ensures overlapping phases by compacting the shallow layers between the initial prints (Byrne et al., 1995). The process is started with DC Probing to drive material (typically rockfill) into the throat of the sinkhole with a penetration pounder until visual refusal is reached thereby chocking the sinkhole throat. The depth of compaction is a function of the weight and shape of the pounder and the drop height (Byrne et al., 1995). In addition, the degree of compaction achievable also depends on the characteristics of the backfill material and the spacing of the DC grid points. The impact shock waves by DC can cause damage to surrounding buildings and infrastructure and this method can only be applied where sufficient distance to neighbouring structures exists. A schematic presentation of the Dynamic Compaction Method used to rehabilitate a sinkhole is illustrated in Fig. 2.

The Dynamic Compaction (DC) Method is applied to:

- Increase the density and bearing capacity of materials when certain subsurface constraints render other methods inappropriate.
- Compact and densify poor subsurface dolomite residuum (wad) or soil layers with a loose consistency to a maximum depth of 10 m.
- Collapse the roof of a cavity located at a depth greater than the bulk excavated area (typically to a depth of 4 m–6 m). This will reduce the cost of excavating to a great depth.
- Collapse subsurface voids within the overburden (Zhou and Beck, 2011). The pattern of ground deformation developed during dynamic compaction often indicates many areas of active and potential sinkhole development (Zhou and Beck, 2011).
- Where the subsurface conditions in the area of the sinkhole presents a safety hazard to workers, the choking of the sinkhole throat by means of the DC Probing Method can create a safe platform to work from.

The DC Method is regarded as a cost effective and practical rehabilitation method to densify material to a maximum depth of approximately 8 m–10 m below natural ground surface (Blom, 2014). Byrne et al. (1995) specifies a maximum depth of 12 m. However, where a competent layer of chert, comprising mainly of gravel and cobbles is present between natural ground surface and the compressible layer (wad), most of the energy expended by the compaction effort is absorbed by the competent chert layer and the material below it is not compacted (De Bruyn and Bell, 2001). To reach the required compaction effort down to a specific depth, the competent layer needs to be removed.

Vibro-compaction methods are not suitable to the South African karst due to the high silt and clay content of the overburden soils and the possible initiation or reactivation of subsurface erosion and potential sinkholes.

3.3. Compaction grouting

Compaction grouting was originally developed in California in the United States during the 1940's to compact beneath and level homes (Brill and Hussin, 1993). In the early 1980's, compaction grouting was first used to treat sinkholes in central Florida, United States (Brill and Hussin, 1993). This method entails the pumping of a mix of sand, cement and water (thick grout) under a specific pressure, down a predrilled borehole, into cavities at depth to fill voids or to densify poor subsurface soils. During the planning phase of a grouting programme on dolomite, for cost estimate purposes, the following grout pressures are typically specified: 0.1 MPa in soil overburden; for highly weathered rock 0.5 MPa and for hard rock 1.0 MPa. The thick grout forms an enlarged bulb or series of bulbs in the soil and displaces the soil immediately surrounding the bulb, thereby increasing its density (Byrne et al., 1995). Based on research done on grouting of the dolomites of the Far West Rand, South Africa, Swart (1991) notes that bulbs can be anything up to a metre and even more in diameter and densification occurs within a radius of 0.3 m–3.7 m around the bulb. However, with compaction grouting, it is generally only possible to obtain an average density of about 90% Modified AASHTO (Byrne et al., 1995).

There are no clearly defined design guidelines for compaction grouting but the design phase generally forms part of the grouting process and comprises monitoring of the degree of improvement being achieved and adapting the grouting process as required (Byrne et al., 1995). In a dolomite environment, unforeseen conditions, not identified during the site investigation, such as the presence and extent of cavities will have a major influence on the volume of grout needed.

Compaction grouting is usually planned as a series of primary and secondary points on a grid with grid centres typically in the 1.0 m–4.0 m range but 1.5 m–2.0 m is more common (Byrne et al., 1995). When compaction near surface is required, the points have to be positioned at the closer spacing (Byrne et al., 1995). The primary points are first drilled and grouted, typically positioned 3 m apart, followed by the secondary points, midway between the primary points, some days later. A tertiary stage may sometimes be necessary. A schematic representation of a grouting grid comprising primary, secondary and tertiary grouting points to rehabilitate a sinkhole is illustrated in Fig. 3.

Distinction is made between, upstage, downstage and a combination of downstage and upstage grouting methods. Upstage grouting is undertaken from the bottom of a predrilled borehole, grout is injected via 1.0 m–2.0 m long stages up to the length of the borehole, raising the grout tube to the top of the next stage on completion of each grout injection (SANS, 2001-BE3, 2012). Downstage grouting is used when the borehole collapses during drilling, preventing the drilling of the borehole to the required depth in a single operation (SANS, 2001-BE3, 2012). The hole is then

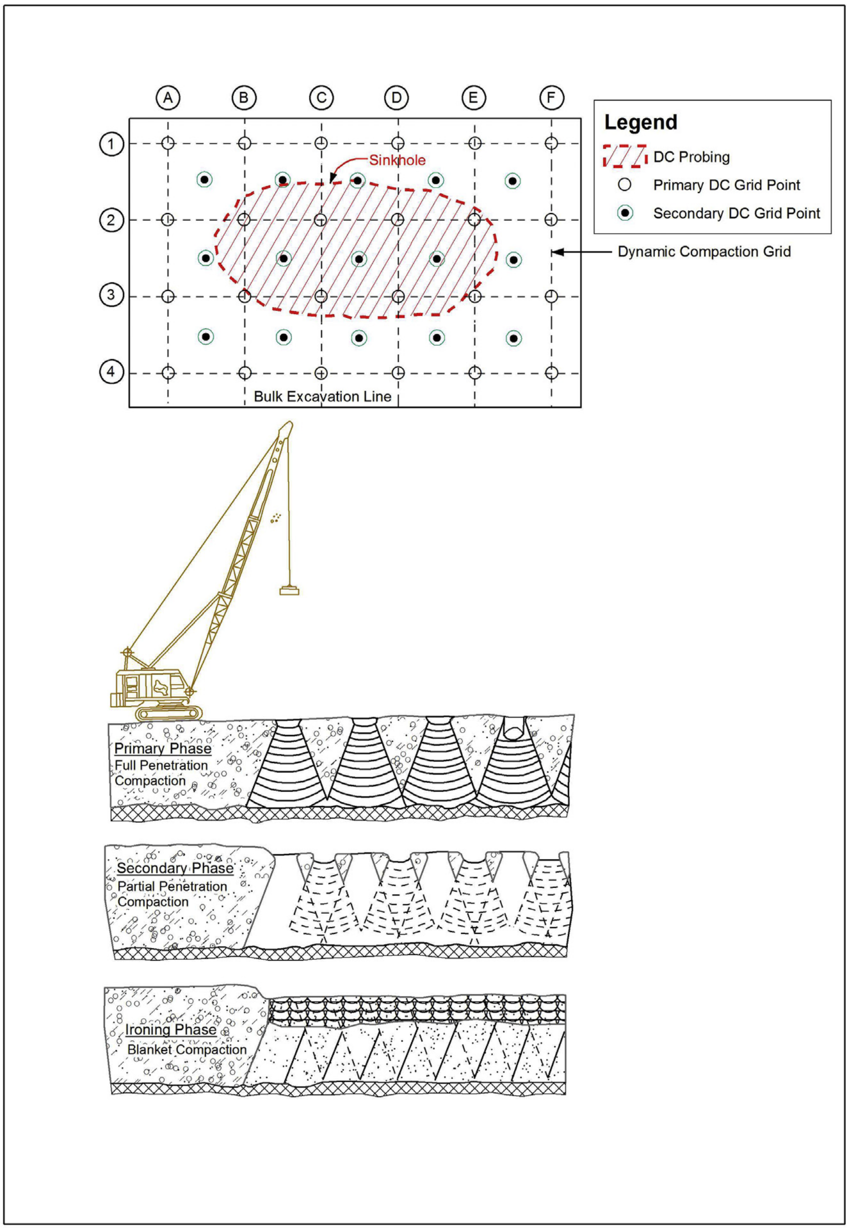

Fig. 2. Schematic depiction of a Dynamic Compaction grid layout and compaction patterns for Dynamic Compaction Probing, primary, secondary and ironing phases (modified after Byrne et al., 1995).

advanced in 1.0 m–2.0 m stages that are grouted and the grout allowed to set for at least 24 h. The hole is then re-drilled and advanced to the depth of the next stage. Combined Downstage and Upstage Grouting is considered where the blanketing layer covering a cavity is thin and a stable working environment needs to be created first by downstage grouting, followed by upstage grouting of the balance of the stratum (Byrne et al., 1995).

The Grouting Method is applicable under the following conditions:

- The method is relatively expensive and is considered where subsurface conditions exist at depths that cannot be treated by means of the Inverted Filter Method or the DC Method.
- To fillvoids above bedrock or cavities within bedrock.
- Improving subsurface conditions to variable depths ranging from ground surface to more than 60 m.
- Improving subsurface conditions close to or below existing structures.
- Densification of compressible dolomite residuum (wad) or loose soils.

Zhou and Beck (2008) describes the use of jet grouting where the filling of a sinkhole throat is too stiff to displace with high pressure. This process involves pumping a fluid grout into the soil with a rotating high-pressure jet which erodes soil and cuts stiff clays and soft erodible rock into gravel to small boulder-sized pieces. Pressures of 30–50 MPa are typically used and the large soil particles, including sand and gravel in the sinkhole filling, mix with the grout to produce a mixed-in-place concrete. This is however not a preferred method used on dolomite, as the grout under high pressure may cause further subsurface erosion of the dolomite residuum forming additional cavities at depth.

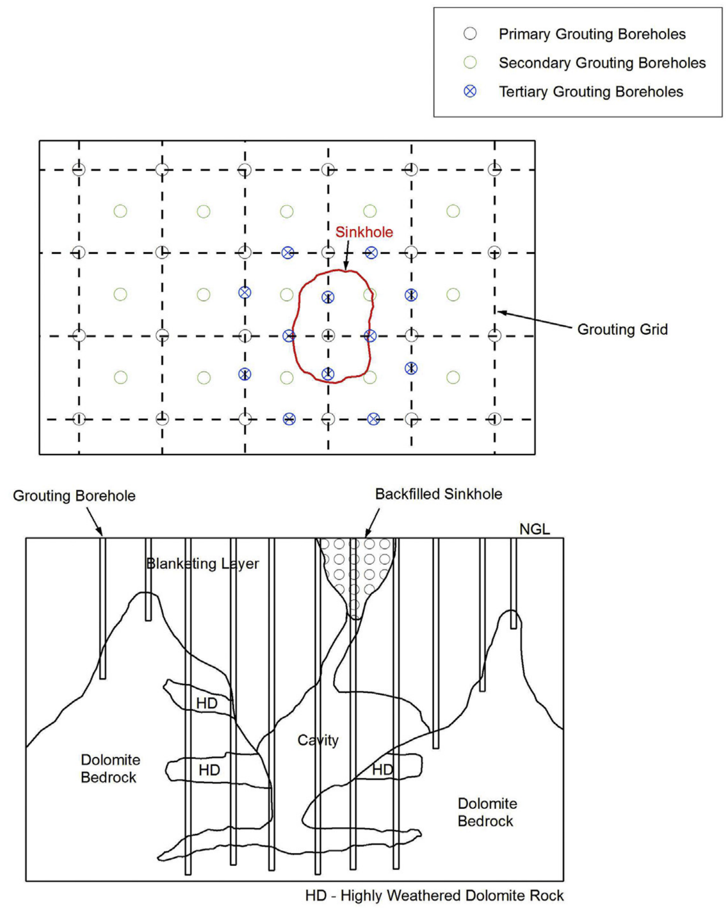

Fig. 3. Schematic depiction of a grouting grid comprising primary, secondary and tertiary grouting points to rehabilitate a sinkhole.

Cap grouting is recommended when a sinkhole is associated with small but discrete fractures on the bedrock surface and the area to be treated is extensive (Zhou and Beck, 2008). Cap grouting uses low pressure (140 kPa or less) to pump lean cement to cover the sinkhole base, fill voids, plug fissures, and displace soft soil (Zhou and Beck, 2008). This cement cover provides support to the upper layers and prevents further vertical groundwater percolation (Zhou and Beck, 2008). Grout hole spacing is typically 0.9 m (Zhou and Beck, 2008).

Slurry grouting may also be used to fill cavities at virtually any depth that can be drilled (Zhou and Beck, 2008). This method involves the injection of various mixtures of very fluid grouts into the ground. It can run along the plane of weakness in the limestone and overburden forming very effective seals; with little to no densification of overburden soil taking place (Zhou and Beck, 2008). Milanovic (2000) recommends large cavities to be filled with rock fills and grout through shafts or large diameter boreholes.

3.4. Combination of inverted filter and dynamic compaction method

A combination of the Dynamic Compaction and Inverted Filter Method is applicable for the following conditions:

- Collapsing of cavities at depth and the chocking of the sinkhole throat by means of the Dynamic Compaction Probing Method up to a specific depth (typically to a depth of 6 m below ground surface), followed by the Inverted Filter Method
- Where an area comprises of sub-areas with sinkholes or underlying deeper voids in the blanketing material are not reachable with an excavator or zones of dolomite residuum (wad) are present in profile to a depth of 10 m.

This is a cost effective and practical rehabilitation method to improve subsurface conditions in areas affected by sinkholes to a maximum depth of between 10 m and 15 m below natural ground level.

3.5. Combination of inverted filter method and compaction grouting

A combination of these two methods may be considered in areas where the sinkhole or subsidence at depth is interconnected with sub-vertical erosion tunnels extending into dolomite bedrock over a distance away from the manifestation at surface of the sinkhole or subsidence. The Inverted Filter Method can be applied to a maximum depth of 12 m. The bulk excavation area will be shaped in a funnel in the area where the sub-vertical erosion tunnel extending into dolomite rock before the Inverted Filter Method commences. After completion of the Inverted Filter Method a grouting programme is undertaken in the area where the sub-vertical erosion tunnel was encountered in the bulk excavated area. The purpose of the grouting programme is to seal off the sub-vertical erosion tunnels extending into dolomite bedrock by means of a grout curtain, or if sufficient funds are available also to fill the cavity.

3.6. Combination of dynamic compaction method and compaction grouting

A combination of these two methods may be considered in areas of major traffic, such as landing strips, roads and railway lines, where a sinkhole occurred and cavernous conditions exist at a depth greater than 10 m. As specified by Byrne et al. (1995) only a 90% compaction effort is typically obtained with compaction grouting. Major roads and railway lines require subsurface layers compacted to at least 95% of Modified AASHTO compaction effort. Therefore compaction grouting can be carried out to fill cavities at depth and Dynamic Compaction conducted to create an engineered earth mattress providing the required bearing capacity.

3.7. Self-compacting concrete or soil-cement mix

Self-compacting concrete comprises of a pumpable concrete mix that requires no external vibration to achieve consolidation, with a 28 day cube strength greater than 5 MPa (SANS, 2001-BE3, 2012). For sinkhole rehabilitation a strength of 10MPa is typically specified.

Soil-cement mix comprises a high slump mix of soil and cementitious binder with a 28 day cube strength greater than 2 MPa (SANS, 2001-BE3, 2012).

Self-compacting concrete or soil-cement mix is used to choke the throat of a sinkhole, plug grykes, or forming a stable working platform at the base of a sinkhole, or for mass filling of cavities or runnels (SANS, 2001-BE3, 2012).

3.8. Chemical grouting

- Permeation Chemical grouting comprises a completely fluid mixture of chemicals [http:/www.earthtech.net/residential/sinkhole-repair/services/chemical-grouting]. It forms a stone-like material by injecting polyurethane based grout along a sleeve port pipe into the subsurface under pressure along a pre-drilled hole. The chemical grout material permeates the soil and solidifies to increase the strength of the stratum and its load bearing characteristics. This method is especially effective in shallow soils and is the typically method used in Florida (USA) to fill sinkhole voids and densifying loose soils that exist within 5 m of the surface.
- Expansive Chemical Grouting involves the injection of expansive foam that fills voids and re-levels foundations. One such method is the URETEK Deep Injection Process [http://uretekicr.com/2013/02/06deep-injection-for-sinkholes]. The expanding geo-polymere is placed exactly at the soil strata depth where soil compaction and densification are needed. The URETEK geo-polymere is injected in the holes (created by a Dynamic Cone Penetrometer (DCP) or DPSH), using a controlled, low-impact process. Multiple injections at varying depths create columns of vertical support. This ‘top down’ injection method is often used on shallow injection applications as it strengthens the upper layer of soil to help contain the pressure of the lower levels of compaction. Once injected, the geo-polymere material expands up to 15 times the material's liquid volume and strengthens to 90% within 30 min. This rapid expansion results in compaction. Through this non-destructive process, soil compaction and densification occurs and void areas are filled and fully stabilized. This method is applicable for the rehabilitation of small to medium size sinkholes located within a depth of 5 m below ground surface.

4. Appropriate rehabilitation method based on the geological model and influencing factors

The investigation and rehabilitation of numerous sinkholes and subsidences on the East Rand, Gauteng Province, made it possible to develop an understanding of the different dolomite environments, their susceptibility to sinkhole and subsidence formation and best practise rehabilitation methods. Generic geological models were developed and are linked to most appropriate rehabilitation methods to serve as a guideline for sinkhole and subsidence rehabilitation in karst environments.

A total of seventeen generic geological models, representative of sinkholes and subsidences on the East Rand were developed, but only nine are presented in this paper with recommended rehabilitation methods.

The sinkhole or subsidence rehabilitation method should not be prescriptive, given the vast number of variables involved. Each sinkhole or subsidence is unique and a site specific set of criteria for the rehabilitation of these features should be developed to ensure proper stabilisation and safe future use of the area. The basic principles that need to be followed in all instances are listed below (Kleinhans and Van Rooy, 2014):

- Ensuring that the cause of the sinkhole or subsidence has been identified and removed;
- The position and extent of the receptacles have been determined and erosion paths sealed;
- The eroded area and possible voids properly densified or backfilled;
- A proper impervious blanket is created;
- Ensuring that all subsurface wet services comply with industry standards;
- Ensuring that proper surface drainage exists.

A comprehensive understanding of the affected area is essential for selecting cost effective and practical rehabilitation measures (Kleinhans and Van Rooy, 2014). It is therefore as a rule, necessary to perform a thorough site investigation of the feature as well as the surrounding affected area. Rehabilitation of only a portion of the affected area will in most instances lead to propagation of the problem (feature) to adjacent areas (Kleinhans and Van Rooy, 2014).

The groundwater in all nine models presented is located below bedrock level and therefore renders the entire unconsolidated profile overlying dolomite bedrock prone to mobilization.

4.1. Impact to a maximum depth of 8 m

Three geological models (Model 1–3) and the most appropriate rehabilitation method for each model are illustrated in Fig. 4 and described in the legend (Table 1).

The various influencing factors considered to determine the most appropriate rehabilitation method for each of the three models are given in Table 2 below.

4.1.1. Reasons for using specific rehabilitation method

- Model 1: The subsurface area requiring improvement extends to a depth of 4 m. Dolomite residuum (wad and ferroan soils) material occurs above dolomite bedrock and down to 1 m depth in grykes. This material is highly susceptible to subsurface erosion and needs to be removed and replace with competent materials. No access constraints exist in the 4 m on both sides of the sinkhole allowing adequate space to undertake bulk excavations down to bedrock depth (3 m) without causing damage to structures.
- Model 2: The subsurface area requiring improvement extends to a depth of 7 m. The removal (and replacement by competent materials) of dolomite residuum (wad) and dolomite floaters

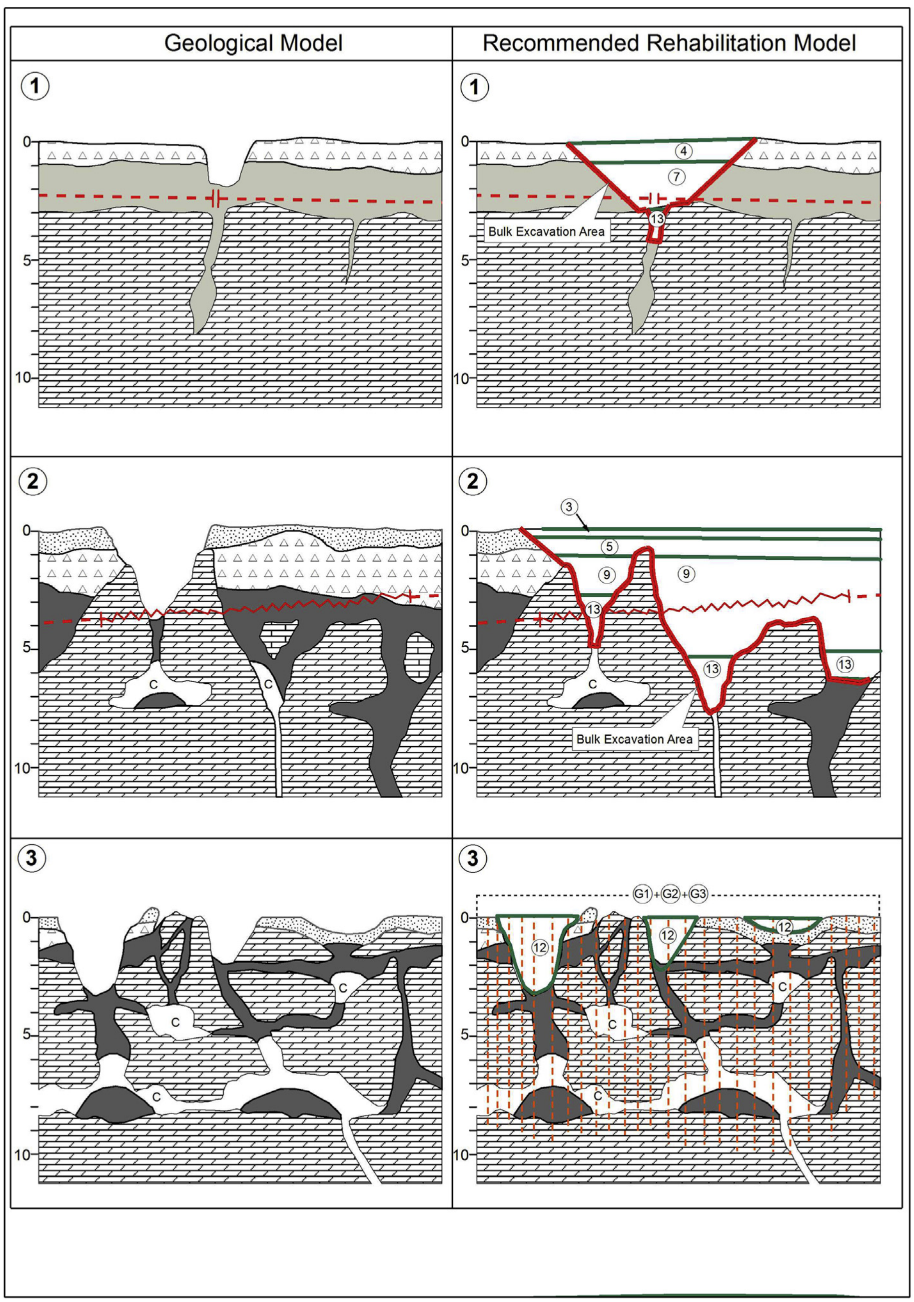

Fig. 4. Generic geological and rehabilitation model 1 to 3.

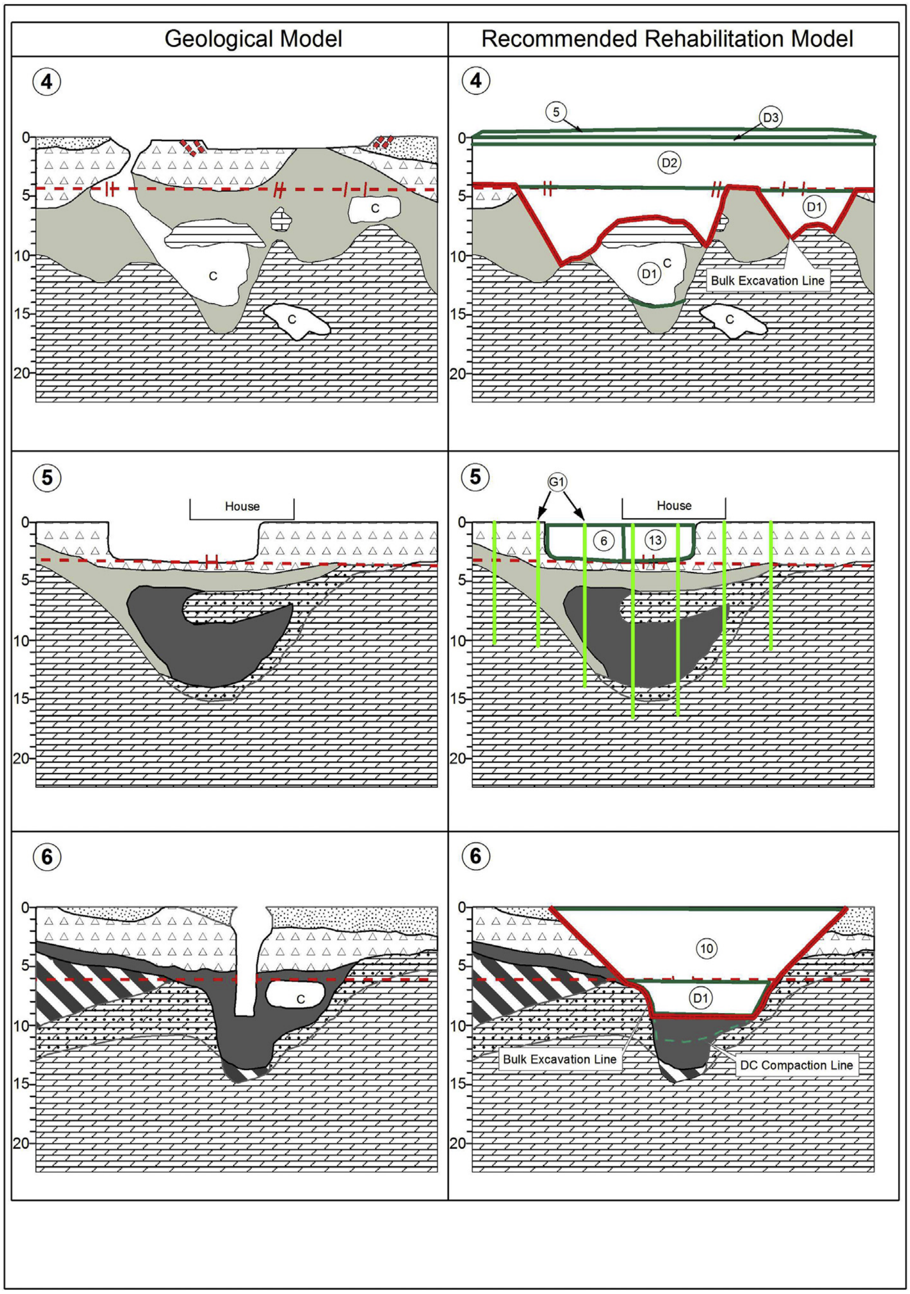

Fig. 5. Generic geological and rehabilitation model 4 to 6.

situated between dolomite bedrock pinnacles, exposure of voids and cavities located within v-shaped grykes and sealing of grykes within 5 m–7 m from natural ground surface. The first 6 m is within reach of an excavator and between 6 m and 7 m depth may be excavated between grykes by hand. No access constraints exist around the sinkhole, allowing adequate space to undertake bulk excavations.

- Model 3: The subsurface area requiring improvement extends to a depth of 8 m–9 m below natural ground surface. The dolomite residuum (wad), voids and cavities are all located along vertical and horizontal joints within dolomite rock and cannot be reached with an excavator. An excavator will only be able to remove the dolomite residuum (wad) down to the first rock interface. The Dynamic Compaction method will also not work due to the presence of dolomite rock above dolomite residuum (wad). The best practical solution to rehabilitate the features and improve the poor subsurface conditions is to fill the sinkholes and subsidence with boulders and soilcrete up to ground surface and then perform a grouting programme. The purpose of the grouting programme will be to densify dolomite residuum (wad) and fill voids and cavities, to ensure the integrity of electrical infrastructure. There are no access constraints for this rehabilitation method.

4.2. Impact to a maximum depth of 15 m

Three geological models (Models 4–6) and the most appropriate rehabilitation method for each are illustrated in Fig. 5 and

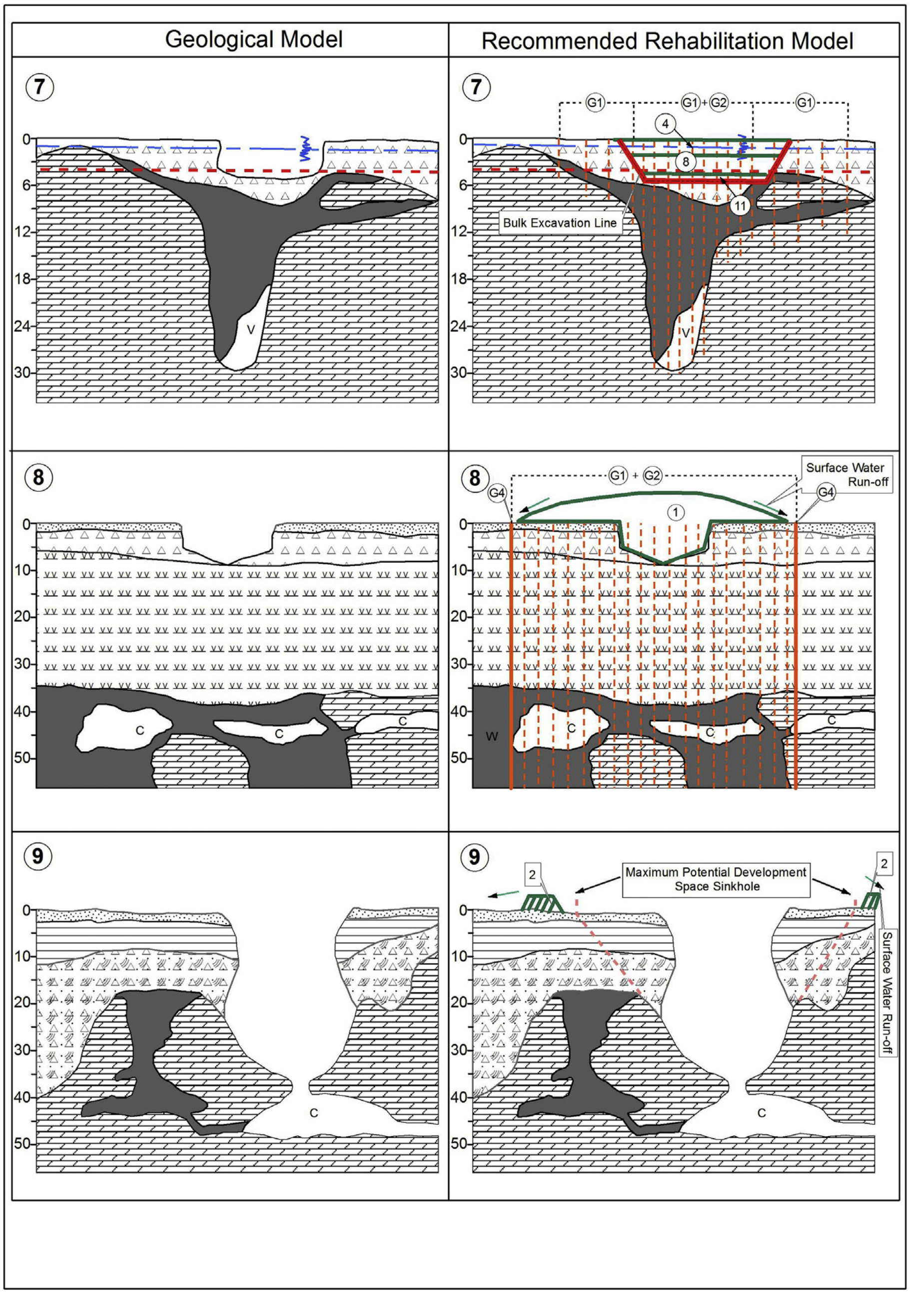

Fig. 6. Generic geological and rehabilitation model 7 to 9.

described in the related legend (Table 1).

The various influencing factors considered to determine the most appropriate rehabilitation method or methods for each of the three models are given in Table 3 below.

4.2.1. Reasons for using specific rehabilitation method

- Model 4: The subsurface area requiring improvement extends to a depth of 15 m and consists of a thick horizon of dolomite residuum, a number of voids and cavities. As the area is proposed for the rebuilding of houses, it was necessary to remove the problematic dolomite residuum material, voids and cavities, and create an engineered earth mattress of between 4 m and 14 m with the Dynamic Compaction Method. The roof over the void was collapsed by means of the Dynamic Probing Method. No access constraints exist, due to all houses being demolished before rehabilitation.
- Model 5: The subsurface area requiring improvement extends to a depth of 15 m and is partially located below a structure. The Inverted Filter Method is typically used to a maximum depth of 8 m and is therefore not a suitable solution. The Dynamic Compaction Method is also not suitable due to the sinkhole partially being located below the structure. The recommended rehabilitation method is the Compaction Grouting Method, as this method can be used to fill voids or cavities below the residential structure and to densify the low density compressible dolomite residuum down to bedrock depth at 15 m. Before the Compaction Grouting Programme commenced the sinkhole was backfilled with 10 MPa mass concrete below the structure and the remaining open portion was backfilled with soilcrete. Access

Table 1
Generic geological and rehabilitation legend for Figs. 4–6.

Geological model – legend	Rehabilitation model – legend			
		Earthworks		
	Number	Material type (G-quality materials, COLTO, 1998)	Layer thickness	Compaction (% Mod AASHTO)
Bulk Excavation Area	1	Bulk unconsolidated G8 – G9 material	Varies	–
DC Compaction Line	2	Compacted G8 – G9 material	Varies	90–95%
Layers of Ground Work	3	G5 material	150 mm	98%
Grout Curtain	4	G5 material	150 mm	95%
Grouting	5	G6 with 5% cement (soilcrete)	150 mm	95%
Maximum Potential Development Space	6	G6 with 5% cement (soilcrete)	Varies	Varies
Ground Cracks	7	G6 – G7 material	150 mm	95%
Sewer Line	8	G6 material	300 mm	95%
Water Line	9	G6 with 5% cement (soilcrete)	300 mm	90–93%
Geology	10	G6 – G7 material	300 mm	95%
Colluvium	11	Sandy gravel & cobbles	300 mm	95%
Residual shale	12	Boulders &soilcrete (3%–5% cement added)	Varies	Excavator bucket
Residual syenite	13	Mass concrete (10 MPa)	Varies	–
Residual chert		**GROUTING**		
Chert gravel & sand	**Number**	**Upstage Grouting Sequence**	**Grout Type**	
Interlayered residual dolomite & shale/syenite	G1	Primary grouting @ 3 m spacing	2 MPa	
Residual dolomite (Ferroan soils or Ferroan soil & Wad)	G2	Secondary grouting midway between Primary positions	2 MPa	
Residual dolomite (Wad)	G3	Tertiary grouting, infilled between Primary & Secondary	2 MPa	
Dolomite floater	G4	Grout curtain	2 MPa	
Highly weathered dolomite		**DYNAMIC COMPACTION (DC)**		
Hard rock dolomite	**Number**	**DC Phase and Material Type**	**Layer Thickness**	
Void	D1	Probing: Building rubble or sandy gravel & boulders	Varies	90–95%
Cavity	D2	Primary DC (5 m grid spacing) & Secondary DC (midway): Sandy gravel & cobbles	1.5 m to 2.5 m	90–98% (200 kPa)
	D3	Ironing	–	90–95%

constraints exist due to the residential structure and overhead electrical cables.

- Model 6: The subsurface area requiring improvement extends to a depth of 14 m; comprising of a thick horizon of dolomite residuum (wad), a void and possible cavity at depth with a sewer line located at 6 m below ground surface. Excavation was therefore required to a depth of 6 m below ground surface to replace the wet service with HDPE pipes. The area of the void and sinkhole was over-excavated to a depth of 10 m. The Dynamic Compaction Probing Method was used to choke the over-excavated sinkhole area up to 6 m below ground surface, followed by backfilling according to the Inverted Filter Method of rehabilitation up to ground level.

4.3. *Impact to a depth of more than 15 m*

Three geological models and the most appropriate rehabilitation method for each are illustrated in Fig. 6 and described in the related legend in Table 1.

The various influencing factors considered to determine the most appropriate rehabilitation method or methods for each of the three models are given in Table 4 below.

4.3.1. *Reasons for using specific rehabilitation method*

- Model 7: The subsurface area requiring improvement extends to a depth of 29 m, including a deep gryke (deep narrow slot) filled with dolomite residuum (wad) and possibly also voids; extending below the residential structure located 10 m away. The Compaction Grouting method is applicable to fill voids or cavities at depth in the area between the sinkhole and structure and below the structure, and to densify the low density compressible dolomite residuum down to bedrock depth at 29 m, to stabilize the conditions below the existing house and surroundings. The Inverted Filter Method is utilised to improve soil conditions within the area of the sinkhole. A section of wet services needed to be replaced, together with a portion of the road.
- Model 8: The recommended rehabilitation method is a grouting programme, including the creation of a grout curtain around the area proposed for improvement. As the dolomite residuum (wad) comprises a large number of voids and dolomite bedrock with cavities from a depth of approximately 35 m below ground surface, receptacles can readily accept mobilized material (including low susceptible materials) from above. The cost

Table 2
Influencing Factors considered for Generic Geological and Recommended Rehabilitation Models 1 to 3.

Influencing factors	Model 1	Model 2	Model 3
Cause/trigger	Broken 110 mm diameter uPVC midblock sewer pipe at 2 m depth, point source.	Multiple cracks and disconnected 160 mm diameter uPVC sewer line. At 4 m depth, 20 m section of pipe malfunctioning.	Ponding and infiltration of run-off surface water. Large surface area affected.
Geological Model Complexity	Simple, homogeneous, nearly horizontal profile.	Intermediate to complex, highly variable bedrock profile.	Complex, highly variable bedrock profile and material susceptible to subsurface erosion.
Blanketing Layer	Chert and dolomite residuum. No voids.	Colluvium, chert and dolomite residuum (wad) with dolomite floaters. Voids encountered.	Colluvium, chert residuum in sub-areas, dolomite residuum (wad). Voids encountered.
Bedrock	Shallow at 3 m, with 1 m grykes and smaller extending to 8 m. No cavities encountered, but possibility of voids in grykes.	Pinnacle dolomite bedrock from a depth of 1 m–8 m, adjoining v-shaped grykes. Cavities present.	Highly jointed vertically and horizontally, joints filled with dolomite residuum (wad). Interconnected cavities encountered. Dolomite bedrock at 8 m–9 m.
Instability Feature dimensions	2 m diameter size sinkhole extending to 2 m depth.	4 m diameter size sinkhole extending to 4 m depth.	4 m diameter size sinkhole extending to 3 m depth, 2 m diameter sinkhole extending to 2 m and 4 m diameter size subsidence extending to 1 m depth.
Impact on Infrastructure	Houses on both sides of sinkhole, 4 m away.	Sinkhole located in sewer servitude and road.	Electrical infrastructure located less than 10 m from affected area.
Rehabilitation Method(s)	Inverted Filter Method.	Inverted Filter Method.	Compaction Grouting Programme.
Land Use after Rehabilitation	Garden areas of residential stands, wet service servitude.	Road, sewer servitude and garden area of residential stands.	Open field in close proximity to electrical infrastructure.

implications related to such a grouting programme will amount to more than 3 million US dollars and consequently is not regarded as a feasible option, considering the current land use (open field with one residential structure affected by the sinkhole). The alternative and more feasible option is to re-locate the residence and demolish the structure on the stand adjacent to the sinkhole and properly fence off the affected area including the evacuated stand. A capping layer of bulk unconsolidated low permeability material is then constructed to at least 1.5 m above natural ground level and extending at least 10 m beyond the sinkhole footprint area. The surrounding area is landscaped to promote good surface water drainage away from the unconsolidated filled sinkhole.

- Model 9: Sterilization of the land is recommended with the placing of a soil berm around the sinkhole area and landscaping of the immediate surrounding areas to ensure effective surface water run-off away from the sinkhole. It will be necessary to fence off the affected area to prevent uncontrolled access. The rehabilitation of instability features of this extent is costly (including backfilling with boulders and soilcrete with finer layers closer to ground surface) and not economically viable, especially when located on agricultural land. The long term rehabilitation measure for instability features caused by dewatering is the proper management and control of groundwater in dolomite compartments by ensuring that groundwater levels are restored to their original level, thereby creating stability. Consideration can only be given to the rehabilitation of existing instability features after the groundwater level has been restored to its original or near original level, if such feature poses a risk to existing structures of importance.

5. Conclusions

Based on the nine generic geological and rehabilitation models

Table 3
Influencing Factors considered for Generic Geological and Recommended Rehabilitation Models 4 to 6.

Influencing factors	Model 4	Model 5	Model 6
Cause/trigger	A 160 mm diameter uPVC midblock sewer pipe, disconnected and broken at a number of points along 120 m section at 4.5 m depth.	Broken 150 mm diameter vitrified midblock sewer line at 3.5 m depth, point source.	300 mm diameter uPVC broken bulk sewer line at 6 m depth, point source.
Geological Model Complexity	Complex, heterogeneous profile.	Intermediate to complex, weathered rock above and within dolomite residuum.	Intermediate to complex, heterogeneous profile.
Blanketing Layer	Colluvium, chert residuum (absent subareas), dolomite residuum with dolomite floaters, residual shale within dolomite residuum (in subareas). Voids encountered.	Chert residuum, dolomite residuum (wad and ferroan soil) with a horizon dolomite rock. No voids encountered. Possibility of voids below structure. Inaccessible for drilling rig.	Colluvium, chert and dolomite residuum, interlayered dolomite and shale in subareas. Void encountered.
Bedrock	Variable depth of 8 m–16 m. Cavities encountered.	Variable depth of 3 m–15 m. No cavities encountered.	Variable depth of 6 m–15 m. No cavities encountered.
Instability Feature dimensions	30 m diameter size subsidence extending to 1 m depth and 1 m diameter sinkhole extending to 1 m depth.	4.5 m × 2 m size sinkhole extending to 2.5 m depth.	4 m diameter size sinkhole extending to 8 m depth.
Impact on Infrastructure	Large number of houses with structural damage and partial subsidence – Demolished.	Sinkhole partially extending below double storey, overhead electrical cables and a water line.	Concrete palisade fence subsided into sinkhole.
Rehabilitation Method(s)	Dynamic Compaction Method.	Compaction Grouting Method.	Combination of Inverted Filter Method and Dynamic Compaction Method.
Land Use after Rehabilitation	Rebuilding of houses and wet services.	Existing residential structure stabilized.	Sewer servitude along provincial road.

Table 4
Influencing Factors considered for Generic Geological and Recommended Rehabilitation Models 7 to 9.

Influencing factors	Model 7	Model 8	Model 9
Cause/trigger	Broken 300 mm diameter PVC water line at 1.5 m depth, point source, additionally 200 mm uPVC sewer line at 4.5 m.	Accumulation and infiltration of surface water run-off against a boundary wall. At ground surface, point source.	Dewatering of the dolomite compartment to 50 m exposing cavities at depth and material highly susceptible to mobilization and subsurface erosion. Followed by ponding of surface water. Potential for the sinkhole diameter to increase.
Geological Model Complexity	Intermediate to Complex, deeply weathered dolomite zone presenting gryke.	Intermediate to complex, thick horizon of low susceptible material above problematic zone comprising dolomite residuum (wad) and numerous voids.	Complex, deep profile susceptible to instability.
Blanketing Layer	Chert residuum, dolomite residuum with thin horizon highly weathered dolomite in subareas. Void encountered during rehabilitation.	Colluvium, chert residuum, residual syenite, dolomite residuum (wad). Voids encountered.	Colluvium, Karoo shale, chert residuum, dolomite residuum (wad) absent in subareas. No voids encountered.
Bedrock	Variable depth of 1 m–29 m, presenting gryke. No cavities encountered.	At a depth of 45 m. Cavities encountered.	Variable depth of 8 m–40 m. Number of inter-connected cavities encountered.
Instability Feature dimensions	3 m diameter size sinkhole extending to 5 m depth. Subsurface erosion at depth over a lateral distance of 20 m along gryke feature.	7 m diameter size sinkhole extending to 5 m depth.	50 m diameter size sinkhole extending to 25 m depth.
Impact on Infrastructure	Partially in road and residential structure 10 m from sinkhole severely cracked with one portion slightly subsided. Residential structure partially located over gryke caused access constraints.	Residential structure located within 7 m of sinkhole, causing access constraints and need to be demolished.	Road in Agricultural Holdings area.
Rehabilitation Method(s)	Compaction Grouting and Inverted Filter Method.	Compaction Grouting Method including a grout curtain. Or a capping layer of low permeability material with sterilization of the stand with the residential structure.	Sterilization of land.
Land Use after Rehabilitation	Existing residential structure stabilized.	Open field and sterilization of stand with residential structure.	Agricultural.

presented for the East Rand it is evident that each sinkhole or subsidence is to a large extent unique, and a large number of influencing factors need to be considered when selecting the most appropriate rehabilitation method.

Rehabilitation methods vary and the method used will depend largely on available funding and the locality of the instability feature, specifically in terms of the current and proposed land use after rehabilitation. The method and materials required to rehabilitate a sinkhole in an undeveloped rural area will be vastly different from that needed to repair a sinkhole or a subsidence below an occupied building or road in a highly urbanized area.

The rehabilitation of sinkholes and subsidences can be evaluated according to the same influencing factors grouped under a specific depth of impact. From a practical point of view distinction is made between impact depths of shallower than 8 m, between 8 m and 15 m and deeper than 15 m.

Influencing factors to be considered for the rehabilitation of all sinkholes and subsidences, include: a) cause/trigger mechanics of sinkhole or subsidence formation; b) complexity of the geological model; c) depth and lateral extent of instability; d) impact on existing infrastructure and e) current and proposed land-use after rehabilitation.

The rehabilitation in all these instances should however have the same end goal to ensure eroded zones and possible voids and cavities are properly backfilled and poor materials such as dolomite residuum (wad) are densified or replaced to create an engineered earth mattress. All affected wet services must be replaced to comply with industry standards and the surface drainage must be away from the area and all proposed or existing structures or infrastructure.

Even though each sinkhole or subsidence is unique, the evaluation of the various influencing factors considered to determine the most appropriate rehabilitation method are the same. The same approach is therefore suggested in other regions affected by sinkholes and subsidences.

Similar or near similar geological scenarios may exist in other dolomite or limestone regions and the various generic geological and rehabilitation models developed for the East Rand may serve as a guideline on the most appropriate rehabilitation methods in similar geological scenarios.

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