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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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ABSTRACT

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).