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Case Study On The Assessment Of Sinkhole Risk For The Development Of Infrastructure Over Karstic Ground

N. Sartain
Arup, Solihull, United Kingdom

J. Mian
Arup, Solihull, United Kingdom

N. O'Riordan
Arup, San Francisco, USA

R. Storry
Bouygues Travaux Publics, Hong Kong

ABSTRACT: Karstic dolomite in the Centurion area of South Africa presents significant challenges to the geotechnical engineer. It has been recognised for many decades that sinkholes can occur in the residual soils overlying the Dolomite, but it is not possible to predict their occurrence or their size. Sinkholes present a significant hazard to infrastructure since they occur suddenly and result in a loss of ground support. In designing the Gautrain Rail Link, routed through the Centurion area, it was necessary to manage this hazard in a rational way. Adopting the maximum possible size of sinkhole that could occur and designing for this eventuality was considered unrealistic in terms of international practice. This paper presents a risk-based approach that was used as part of the design for the section of Gautrain running over the dolomites to demonstrate that sinkhole risks have been made as low as reasonably practicable. A quantitative risk assessment was undertaken to model numerically the consequence and likelihood of sinkhole occurrence. This approach enabled the risk from sinkholes to be quantified and was used to help define the design requirements for the infrastructure in respect of this hazard.

Keywords: Dolomite, Karst, Sinkhole, Risk management, Infrastructure

1 INTRODUCTION

The Gautrain Rail Link project connects the centre of Johannesburg with Pretoria (via Centurion), and the Oliver Tambo International Airport with Sandton. Civil construction works were substantially completed by the end of 2010 with the section between Johannesburg and Pretoria expected to be operational by mid-2011. Within the Centurion area of Pretoria the route crosses 15km of dolomitic ground, of which 5.8km are on viaduct. There are very significant geotechnical challenges associated with the design and construction of a high speed railway on the dolomite (such as extremely variable and often very deep rockhead, rock pinnacles and floaters, and residual soils that can be very strong and stiff close to the surface yet extremely weak and soft at great depth), but this paper considers only the particular hazard posed by sinkholes. The consequence of a large sinkhole occurring that may result in the failure of part of the railway infrastructure could be extremely serious, from both a safety and economic perspective.

The alignment could not avoid the dolomitic ground, so the designers had to consider for what size of sinkhole it was appropriate to design, balancing the requirements of capital cost, operational cost, passenger safety and uninterrupted railway operation. This paper describes the risk process undertaken to permit this decision to be made in an informed and robust manner.

2 THE SINKHOLE PROBLEM

The dolomite of the Centurion area of South Africa is 2500 million years old. It has been subjected to long periods of chemical weathering (dissolution by water) resulting in the formation of a thick, and highly variable 'residuum' over the rock. The residuum comprises 'wad' (a low density, weak material that is highly erodible and compressible), and very strong chert. The weathering of the dolomite has resulted in a highly pinnacled rockhead that in places is at the ground surface but elsewhere is at >100m below ground level. The residuum (Wagener 1982) is often quasi-stable and sinkholes are a recognised ground hazard in the area. Significant efforts (Waltham *et al.* 2005) have been made to understand the conditions under which they occur, the processes that cause them and the influence of human factors on this (for example leaking wet services or lowering of groundwater). Nonetheless, neither the location of future sinkholes, nor their dimensions can be reliably predicted. It is, however, possible to estimate their maximum possible extent (Buttrick *et al.* 2001).

Sinkholes (defined as 'dropout' sinkholes, Waltham & Fookes 2003)[1] are hazardous because they open suddenly resulting in an immediate loss of support to foundation systems. Sinkholes have been responsible for a number of deaths and damage worth many millions of Rand in the study area.

Sinkholes in the Centurion area vary from the very small (1m diameter, 1m depth) to the very large (up to 45m diameter, 30m depth). The sinkhole size is a function of many factors including the depth to rockhead, the geometry of the rockhead, the properties of the overburden and the depth to groundwater (Buttrick *et al.* 2001). Their formation is the result of washing out of overburden into cavities in the dolomite rock, and for this reason they can be triggered anthropogenically, due to failures of 'wet' services (drainage, water supply, swimming pools etc.) or to groundwater drawdown resulting from pumping for agriculture use for example. Schöning (1990) found that 94% of sinkholes in wider Centurion area were in developed areas, and by implication were attributable to anthropogenic triggers. Other authors (Waltham *et al.* 2005) consider that this could be an underestimate. Additionally, and significantly for this study, large sinkholes (greater than 15m) have only been observed in areas where groundwater abstraction has resulted in significant drawdown of the water table.

3 EXISTING METHODS FOR MANAGING SINKHOLE HAZARD IN THE CENTURION AREA

Existing methods for controlling sinkhole risk around Centurion have focused on mitigating the consequence of sinkhole occurrence by stipulating the type of development permitted in areas classified by a risk rating after Buttrick *et al.* (2001). This approach was developed primarily in relation to planning for building development. However, when designing linear infrastructure such as rail routes, re-routing is rarely a feasible option for avoiding a specific hazard, given the multiple constraints on the route.

Initial design proposals for the Gautrain were to deterministically estimate the largest size sinkhole that could occur along the alignment and to design the infrastructure to cope. This was applied first to the design of at-grade infrastructure for which the appropriate sinkhole parameter is diameter. Using this deterministic approach, 30m was proposed as the design diameter and it was found that the impact on the construction cost due to a design having to cope for a 30m diameter sinkhole occurring beneath the alignment was extreme. Furthermore, after very long and detailed studies it appeared that for the elevated section founded on piles to rock no viable solution would be found.

A contractor's study for the Gautrain project estimated that the frequency of sinkhole occurrence with diameter >15m was 10^{-5}/km^2/annum. Designing for 30m diameter sinkholes, and incurring the associated costs, was therefore considered to be an excessively risk averse approach and outside normal international practice to risk management.

4 RISK-BASED APPROACH TO DESIGNING FOR SINKHOLE OCCURRENCE

A different approach was required, one which achieved a better balance between whole-of-life risk and capital cost. A number of expert groups were convened to review the sinkhole risk in order to determine realistic and robust design requirements.

The risk management of the Gautrain project was based on the approach of HSE (2001), which presents the concepts of intolerable risk, tolerable risk and broadly acceptable risk.

Intolerable risks must be addressed and are not permitted. Broadly acceptable risks are those which are sufficiently low so as not to be of concern. Tolerable risks lie between intolerable and broadly acceptable risks, and HSE (2001) requires that such risks are made 'as low as reasonably practicable', ALARP, Fig. 1.

[1] As well as 'dropout' sinkholes, there are also 'suffosion' sinkholes (Waltham & Fookes 2003) which are essentially subsidence events. They are also problematic for structures on dolomite, but are not considered in this paper. Only 'dropout' sinkholes have been considered since their sudden occurrence carries much greater likelihood of failure of infrastructure.

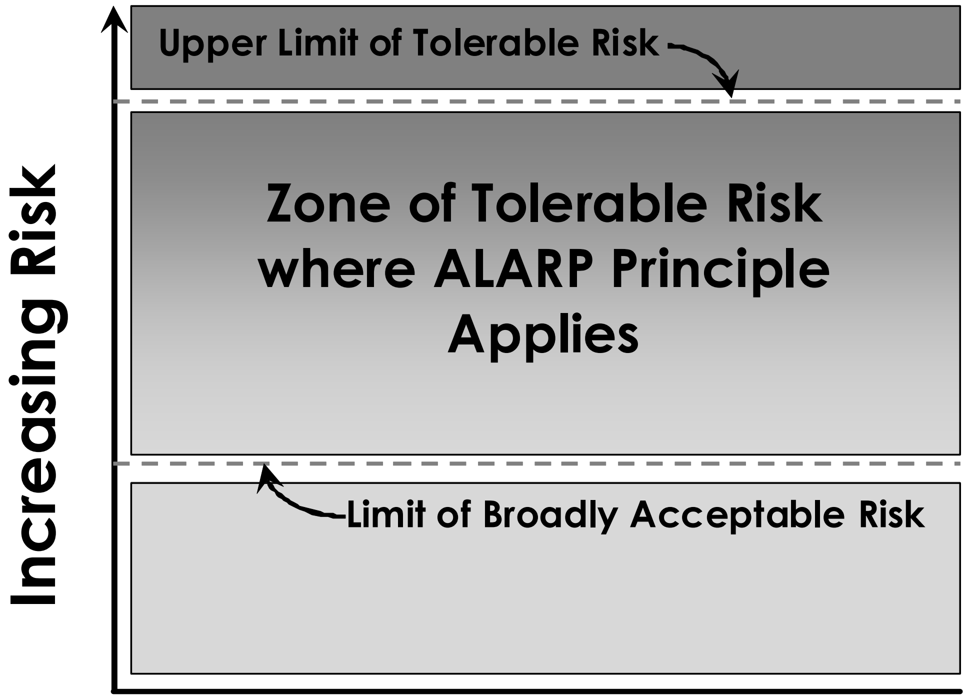

Figure 1. Tolerability of risk and the ALARP principle

The principle of this approach was to produce a design for which it could be demonstrated that the safety risk associated with sinkhole occurrence was tolerable. The threshold for intolerable risk (for all project risks) was defined quantitatively based on a review of literature (The Royal Society 1992; HSE 2001; Jonkman *et al.* 2003) as an annual frequency of passenger fatality of 10^{-5}. This paper presents one branch of the expert review in which a quantitative risk assessment (QRA) was undertaken to estimate the sinkhole risk and to identify the required performance of the mitigating measures using the ALARP principle. It uses the terminology presented in Free *et al.* (2006) when discussing hazard and risk.

4.1 *QRA*

The following paragraphs describe the QRA that was undertaken.

Initially it was necessary to define a model to describe how the occurrence of a sinkhole can lead to a negative consequence. Figure 2 presents a simplified model for the sinkhole problem, showing the stages of the analysis on the left, the steps that contribute to the outcome in the middle, and how each step was modelled on the right.

From the designer's point of view, it is important to note the effect the structural response has on the outcome. Sinkholes, just like earthquakes or landslides, do not have an inherent risk if they have no consequence. It is the interaction of the hazard with the population and its economic interests that gives rise to the risk, and it is the response of the infrastructure to the hazard that ultimately determines the level of risk.

Probability density functions were assigned to each uncertain variable, and then simulated using a Monte Carlo approach.

4.2 *Defining the sinkhole hazard*

The specific hazard under consideration is the sudden loss of support to foundations due to sinkhole formation. For shallow foundations this is be a loss of vertical support, whilst for piled foundations this could be primarily a loss of horizontal support accompanied by a lateral thrust into the newly-formed sinkhole. The level of risk is controlled by the size of the sinkhole, but the appropriate size metric adopted may change depending on the situation under consideration. Only the diameter is considered below, by way of example.

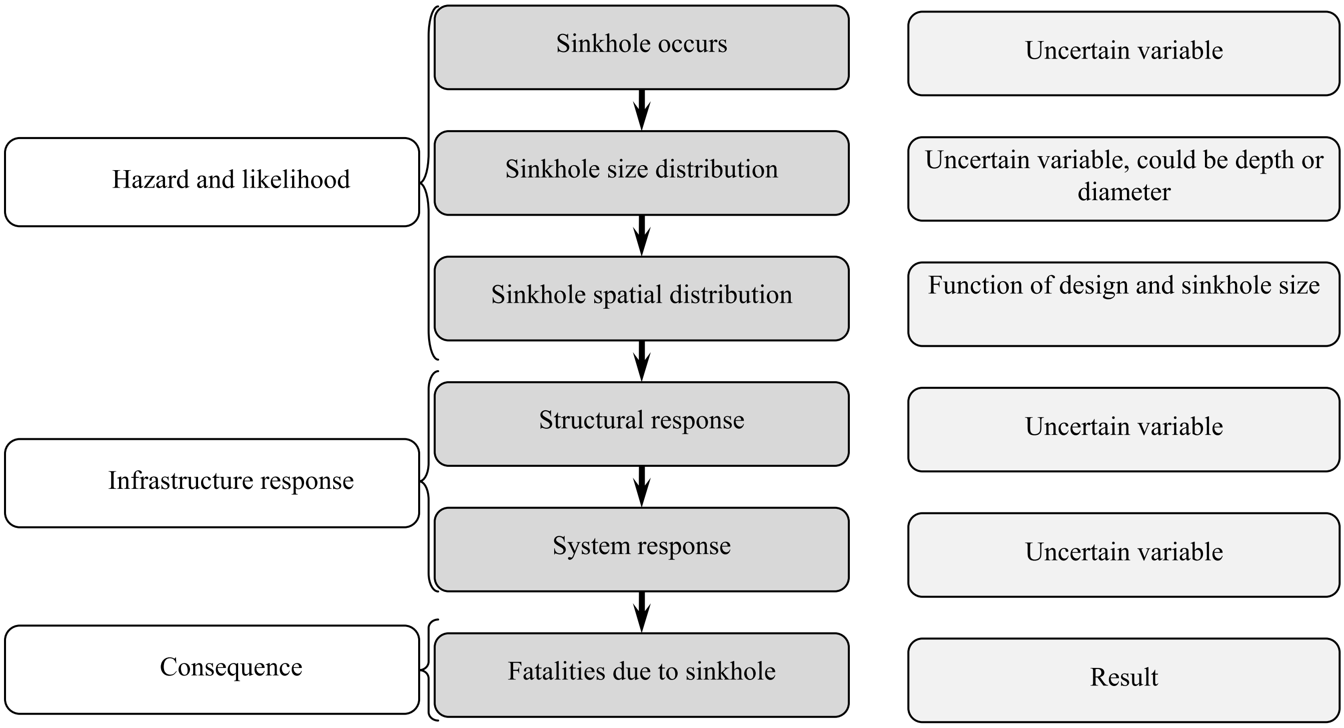

Figure 2. Example risk model for QRA for the sinkhole effect on infrastructure

A database detailing 287 sinkholes was acquired by the Gautrain project. The data were not complete, and careful interpretation was required to avoid misleading conclusions.

Figure 3 shows the sinkhole diameter distribution presented as a probability distribution for the sinkholes in the database. Note the peaks in the data at 5m, 10m, 15m etc. indicating that a significant amount of the data is estimated and rounded up or down, depending on the observer.

It appears that large sinkholes (>20m) are significantly over-represented in the database. The main reasons for this observation are thought to be:

– The dataset has been collected reasonably thoroughly in the past quarter-century (approximately), but includes larger sinkholes (that people would have remembered) from a greater time period. In this scenario the largest sinkholes will be over-represented and this is consistent with the data. This is analogous to the catalogue completeness in seismic hazard studies; the older the earthquake records, the higher the threshold of earthquake magnitude at which the catalogue is considered complete.
– Larger holes are more likely to suffer additional collapse of initially vertical walls which will tend to increase their size.

Figure 3 also presents the exponential probability density function (PDF) considered to best represent the available data and that was adopted for use in the QRA.

4.3 *Defining the sinkhole likelihood*

Having established a diameter distribution for sinkholes in the Centurion area thereby defining the hazard, it was necessary to determine the frequency of sinkhole occurrence, i.e. the likelihood of the hazard occurring. The rate of formation of new sinkholes (RNS) is measured in new sinkholes per area unit per time unit.

Sinkholes occur primarily as a result of failures in wet services or of groundwater drawdown (Waltham *et al.* 2005). RNS therefore depends not only on the natural geological and hydrogeological condition of the site, but also on factors such as the quality and density of wet services, regulation and control of wet services, the population density and groundwater abstraction. It is very difficult to estimate accurately the historical frequency of sinkhole occurrence because these factors have all changed over comparatively short timescales. Future RNS will depend on the existing and future wet infrastructure at the site under consideration. For major new projects, however, RNS can be expected to reduce significantly compared to recent years since the importance of these human influences is now understood and the budget for controlling them can be made available. For smaller projects, it is possible that RNS could increase as existing wet services age and degrade.

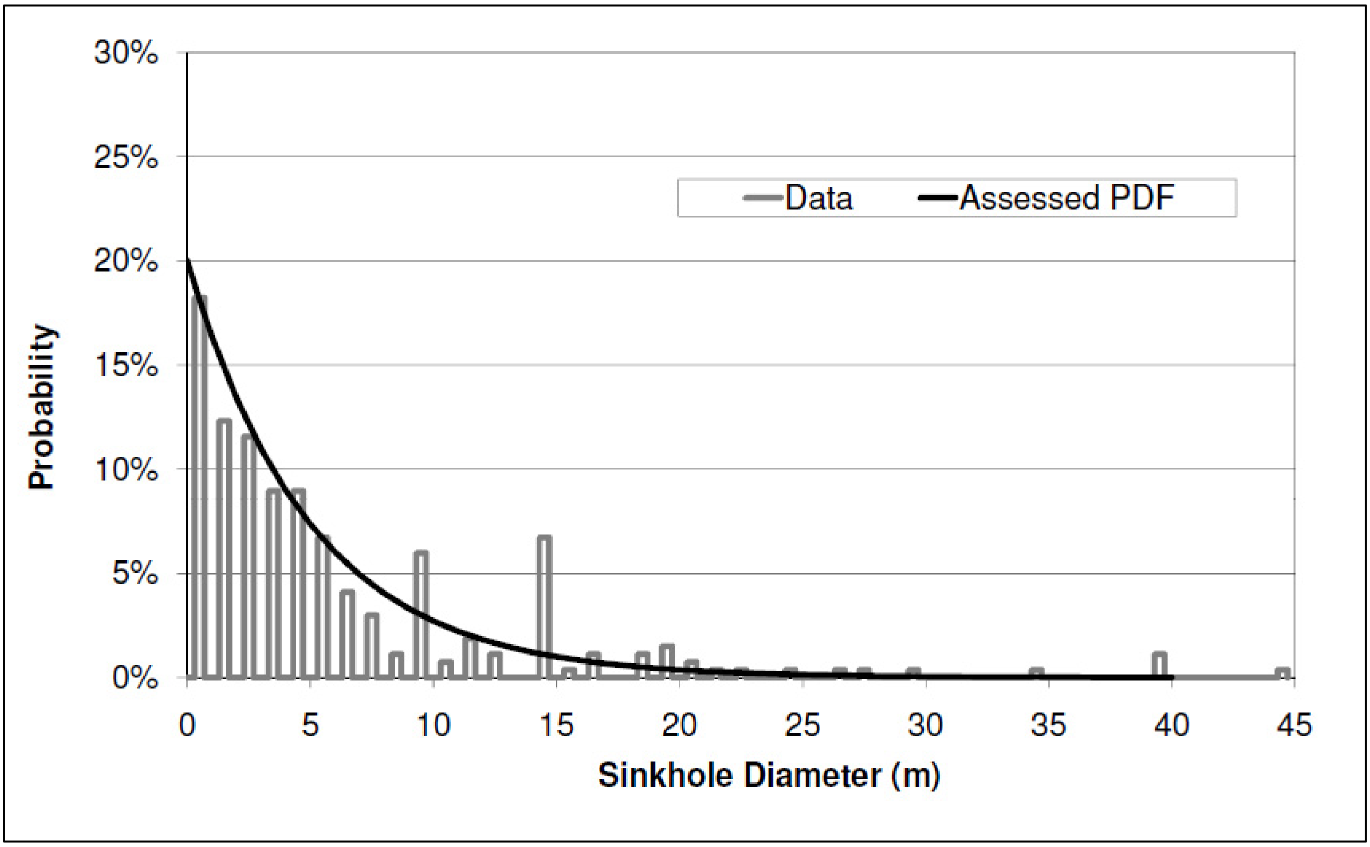

Figure 3. Sinkhole diameter distribution from sinkhole database in Centurion area

So, whilst it was not possible to calculate the future RNS, it was estimated from a review of the literature (Waltham *et al.* (2005), Waltham & Fookes (2003), The South African Department of Public Works (2004), Buttrick and van Shalkwyk (1998)) and by assessment of the available data.

A range of RNS was modelled in the QRA between the estimated upper and lower bounds of the RNS. The QRA therefore assessed the likely outcomes if existing conditions were observed. The effect on the risk of significantly improved management of 'wet' services within the railway corridor was left as a design decision to be taken later.

4.4 *Consequences of sinkholes*

The consequences of a sinkhole occurring adjacent to, or beneath, a structure are a function of the response of the structure to the sinkhole event. For the sections of the Gautrain at-grade and on embankment the engineering solution was to place the track in a reinforced concrete U-trough – effectively an at-grade bridge designed to span sinkholes up to the 'design' diameter.

The effects of the (assumed random) spatial distribution of sinkholes was included in the model. The relative likelihoods of small nearby sinkholes as well as large but further away sinkholes on the U-trough were modelled.

To simplify the QRA, the U-trough was assumed to have a binary response – for all sinkhole events below the 'design' diameter it did not 'fail', and for all events greater it did 'fail'. 'Failure' was defined as loss of performance sufficient that if a train passed over it, there would be sufficient movement that derailment of a train with consequent fatalities was possible.

Figure 4 presents sample results from the QRA for various confidence intervals. It shows the annual risk of a sinkhole occurring that could cause structural failure of the U-trough at various confidence intervals for increasing size of 'design' sinkhole diameter. The spread of confidence intervals is due to the use of PDFs as inputs within the logic tree.

4.5 *Design decisions and requirements for ALARP*

Having estimated the frequency of failure of the U-trough it was necessary to determine the diameter of sinkhole that the U-trough was designed to span, and what further mitigation measures would need to be implemented in order to achieve a tolerable risk at acceptable cost.

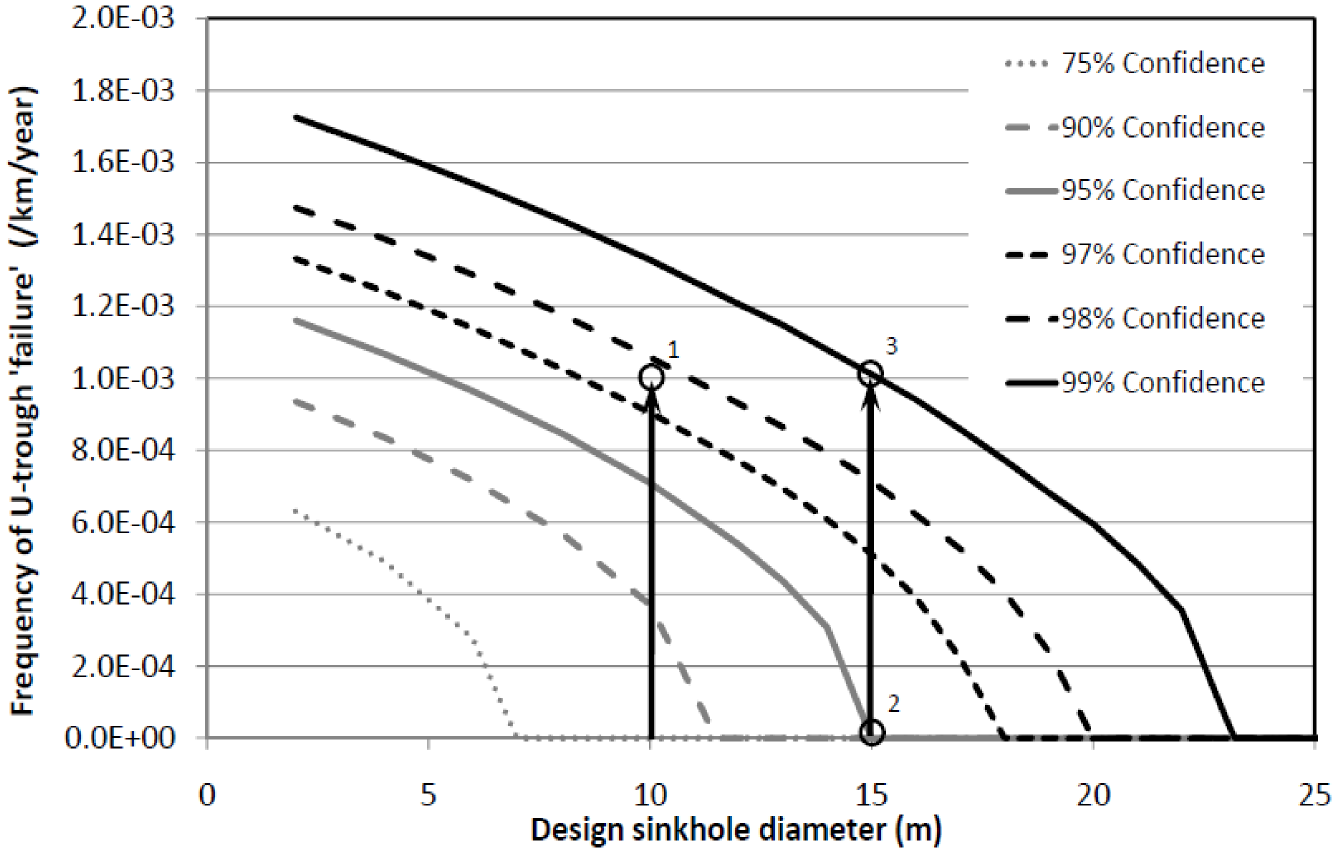

Figure 4. Result of QRA for U-trough showing relationship between frequency of 'failure' and 'design' sinkhole diameter, assuming existing 'wet' service conditions

Figure 4 shows that if the U-trough were to be designed to withstand a 10m diameter sinkhole, then the frequency of failure is around 10^{-3}/km/year with between 97% and 98% confidence (note 1 Figure 4), assuming similar RNS to observed in the recent past. Increasing the 'design' sinkhole diameter increases the confidence of a given frequency of failure, or for the same frequency of failure increases the confidence level.

So the study has established that for reasonable 'design' diameters, and for existing conditions, the frequency of failure is rare (approximately once in a thousand years) with a high degree of confidence, but not so rare that additional measures are not required to bring the risk down to tolerable levels (i.e. to levels where the annual frequency of passenger fatality is less than 10^{-5}.

Construction cost increases exponentially with increasing 'design' sinkhole size, but Figure 4 shows that designing for progressively larger sinkholes does not reduce the frequency of failure significantly, unless the confidence interval chosen for design is very close to the percentile of the 'design' diameter on the PDF in the QRA model. Therefore it was found to be cost effective to design for a smaller 'design' sinkhole diameter and to invest in robust sinkhole mitigation measures that would have a much greater impact on reducing the risk. For example, controlling the wet services could reduce the frequency of sinkhole occurrence from that adopted in the model by more than an order of magnitude. The benefit of the QRA was that it framed the risk in a way that enhanced the ability of the design team to make such decisions.

At this point the various expert groups that had been working on the problem were reconvened. It was determined that the most appropriate 'design' sinkhole diameter for the design of the U-troughs was 15m, for the following reasons:

– This study had shown that a 15m 'design' diameter gave a tolerable risk (actually zero risk) with 95% confidence (note 2 Figure 4), even assuming existing groundwater management, and a frequency of failure of approximately once in a thousand years with 99% confidence (note 3 Figure 4);
– The findings from other groups were that sinkholes of diameter >15m were only observed in areas of significant groundwater drawdown and therefore the actual RNS for these diameter holes was much lower (by up to two orders of magnitude) than predicted from the dataset studied. This difference appears very large, but note that the frequency used for the base QRA was estimated from data collected over recent decades at a time of relatively poor water management and that large sinkholes were over-represented in the dataset. These factors account for the bulk of this difference.

- There was a practical aspect of railway operation to consider. The 'design' sinkhole needed to be a rare event such that the robustness of the design to smaller and much more likely sinkholes was at a level where interruptions to the train operations were at an acceptable level.

To complement this choice of 'design' diameter the following measures were implemented following the principles of ALARP to ensure tolerable risk from sinkholes:

- Replacement (and sleeving) of utilities affected by the work within the rail reserve to minimise the chance of leakage
- Piezometers were installed along the route in the dolomite (and within the rail reserve) which will be monitored regularly and compared against predefined trigger levels to give an early warning of pumping/water drawdown
- Dynamic compaction was undertaken throughout the route as an investigation technique and full dynamic compaction treatment where the ground was considered to be collapsible in the top 10m or where soft areas were identified by the investigation work
- A monitoring system placed below the embankment was set up in the three highest risk zones (determined from investigations into the overburden) which acts as an early warning in the event that the ground settles/collapses beneath the embankment

The combined effect of these measures can be estimated to reduce the risk from sinkholes by three to four orders of magnitude. In this way the consequences of sinkhole occurrence on the Gautrain project were controlled by the engineering design and the risk from sinkholes was demonstrated to be tolerable, following the principles of ALARP, at lower cost than designing for sinkholes with diameter 30m.

The same approach was subsequently applied on the project when considering the design of viaduct foundations in the Dolomite. The detail of the analysis was different since for deep foundations the depth of sinkhole was found to be more significant than the diameter, and different mitigations were needed but the same principles were used.

5 CONCLUSIONS

It has become necessary in the case of Gautrain, and will become necessary for other infrastructure works, to develop the Dolomite land in the Centurion area. The Dolomite has a complex karst geology and sinkholes occur in the residuum materials above the rockhead.

Sinkhole hazard and likelihood were defined quantitatively using data of historic sinkhole events in the area and an understanding of the geology, hydrogeology and the significant role wet services play in determining sinkhole occurrence. The response of the infrastructure to sinkholes was determined quantitatively.

A risk model combined with Monte Carlo simulation was used to define the events leading to negative economic or safety consequences of sinkholes in a QRA. The outcome of the QRA was used to inform important design decisions on the Gautrain. By using the methodology presented in this paper, combined with the use of expert judgement, it has been possible to avoid designing for the worst-case sinkhole scenario through quantitative estimation of the risks and capital costs of the available engineering solutions. The design was undertaken to the ALARP principles set out in HSE (2001) and the risk from sinkholes to the Gautrain was reduced to tolerable levels.

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