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The use of ground penetrating radar to identify karst terrain features in the Northern Territory

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ABSTRACT: Karst terrain presents challenges to large infrastructure such as airfields due to the presence and development of sinkholes and cave systems leading to rapid ground collapse and damage. vehicles and potentially a risk to life. A ground penetrating radar (GPR) survey was performed to investigate the presence of caves and sinkholes formed from karst process near an airfield in the Northern Territory, Australia. GPR was undertaken along a series of 5m nominally spaced lines totalling approximately 750 linear km using a towed shielded low frequency antenna. GPR pulses were transmitted into the ground and reflections recorded at subsurface interfaces with contrasting electrical properties (dielectric and conductivity) such as boundaries between soil and rock. Interpretation of GPR records and observations were used to track and digitize reflections from subsurface layers as well as to identify subsurface features. This paper describes an innovative and reliable method of identifying sinkholes and caves using GPR.

1 INTRODUCTION

1.1 *Location of investigation*

Katherine is located approximately 320 km to the south east Darwin within the Northern Territory

1.2 *Geological setting*

The geology of the area to the south of Katherine is dominated by the Cambrian aged Tindal Limestone (Kruse, 2013). The Tindal Limestone was deposited in the Daly Basin, principally in an open shelf environment of unrestricted circulation and varied fauna. Proven to be over 180m thick, the limestone is a flat-lying unit of grey mottled, onkoid, ribbon and bioclastic limestone with minor intercalations of maroon-green siltstone or dark grey mudstone and associated cryptomicrobial laminite and stromatolitic boundstone (Kruse, 1994).

1.3 *Karst and chemical weathering of limestone*

Limestone is soluble in water and chemical weathering results in only very small insoluble residues. Chemical weathering of carbonate rocks including limestone can produce landforms such as sinkholes and caves. Underground fractures are enlarged by chemical dissolution by slow-moving groundwater. Over time, the initial cracks in soluble rocks are enlarged into wide fissures and then into open caves that can carry all-natural drainage underground (Waltham, T. 2002).

The dissolution of limestone is a very slow process. In the UK rates of dissolution were calculated as being 0.041 to 0.099 mm annually, whilst in the eastern United States researchers have suggested rates of 0.025 to 0.040 mm per year (Bell, 2007).

Surface hollows or closed depressions are the com-mon landform of a karst terrain. They may be 1m to many kilometers across and 1m to 300m deep with sides that range from gentle slopes to rocky cliffs. They may contain sizeable sinking streams or rivers or may absorb all rainfall percolation and fissure flow. To the geomorphologist these closed hollows are known as “dolines”, but most engineers refer to them as sinkholes (Waltham T. , 2009). Six types of sinkholes have been classified based on the process by which they develop (Waltham et al, 2005) (Figure 1).

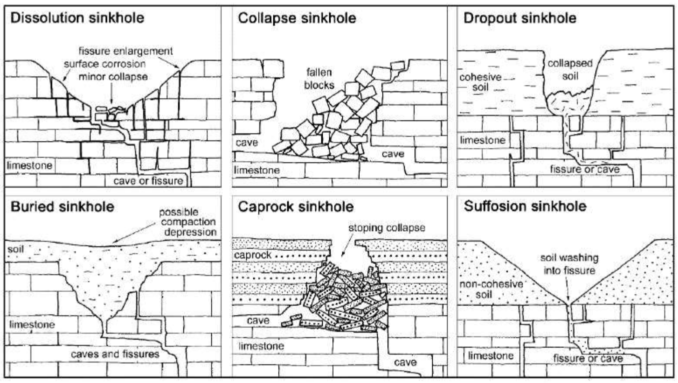

Figure 1 A classification of sinkholes, with respect to the mechanisms of the ground failure and the nature of the materials which fails and subsides Waltham, T and Fookes, P. (2003).

Underground drainage through a karstic limestone is largely through conduits that have been enlarged by dissolution; those large enough to be entered by humans are caves, which are interconnected with smaller fissures. Caves may form anywhere within a limestone mass where there has been through-draining of groundwater and can be very complex. Most cave systems are multi-phase, with an early network of caves modified and entrenched by a later phase of cave building. Older caves may be modified by roof breakdown debris, stalactites and stalagmites from calcite precipitation and saturated percolation waters. Once groundwater flow is established, cave passage enlargement is mainly by dissolution via drainage waters containing carbon dioxide. A cave passage 1 m in diameter may be formed from an initial fissure within about 5000 years (Waltham, 2009).

1.4 *Engineering implications of karst*

At the ground surface irregular or pinnacled rockhead can create difficult ground conditions as the depth to rock head beneath ground level may vary by many meters over a very short lateral distance.

Construction over a cave relies on the integrity of its rock roof under imposed load. Strong beds of in-tact limestone are stable in very thin spans but the degree of fracturing and fissuring must be assessed for each site and inspection of a cave roof may indicate variance from the guide ratio. Most caves are however stable in their natural state; conventional engineering would require little or no roof support in excavated tunnels or caverns of comparable sizes (The engineering classification of karst with respect to the role and influence of caves, 2002).

2 KARST IN THE KATHERINE REGION

2.1 *Katherine region*

The seminal work on the description, mapping and characterization of sinkholes in the Katherine region was undertaken by Karp (2002) and published by the Department of Infrastructure, Planning and Environment NT Government.

According to Karp (2002) the typical method of sinkhole development in the Katherine area is shown in Figure 2. Collapses are usually caused by an increase in downward movement of the surface water. Stage 1 shows the surface runoff concentrated in drains and impoundments increasing the downward pressure of water. This results in the piping of saturated soil into opening in the limestone. Stage 2 shows the collapse of soil arches due to loading of the surface by ponded water or vibration of the surface associated with blasting or road transport.

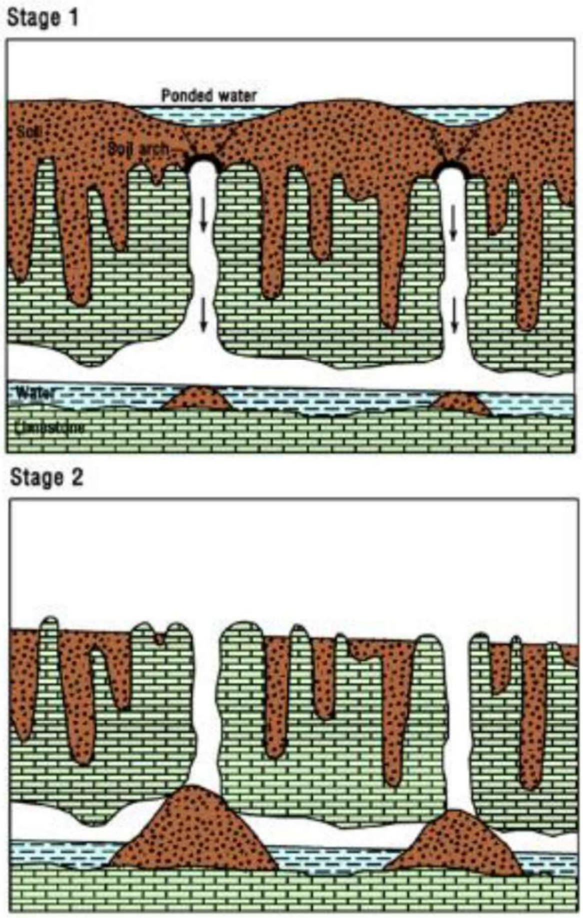

Figure 2 (Stage 1 and 2): Schematic diagram showing mechanism of sinkhole collapse similar to those observed along the Stuart Highway (SH1) south of Katherine (Karp, 2002)

2.2 *Cutta Cutta Caves and SH1*

Cutta Cutta Caves Nature Park is located 30 kilometres south-east of Katherine. The Park's total area is 1499 hectares, comprising NT Portions 1797 and 786. The Park's main feature, the Cutta Cutta Cave is presently the only cave in the Northern Territory that is open for public tours. This and other caves in the Park have been known and visited since the early 1900s. (Parks and Wildlife Commision, NT GOV, 2000)

There are at least three major cave systems on the Park that have underground passages that exceed 500 metres. Another twelve or so caves contain passages of 100 metres or more and perhaps another fifty smaller caves have passage lengths greater than fifty metres.

A good example of a surface sinkhole was inspected approximately 5km north of the caves and ap-proximately 50m from the SH1 just south east of the bend between the Caves and RAAF Base Tindal (53L, 224354mE, 8390115mN). These sinkholes comprised exposed, rounded, vertical limestone pinnacles and towers approximately 10m wide and 4m deep. Red soil, typically comprising clayey sands and silts, filled the voids between towers (Figure 3).

Figure 3 – Sinkhole development near Cutta Cutta Caves, just off SH1

2.3 *Katherine Airfield*

Investigative work to examine the presence of karst and solution features at Katherine Airfield are numerous. At the site, karst morphology typically presents as shallow sinkholes but some larger sinkholes are known to operatives. No cave systems have been recorded. It is considered that the sinkholes have formed at the airfield due to a combination of suffosion and collapse and as a direct result of an increase in downward movement of surface water, resulting in piping of saturated soils into the fissures and between buried pinnacles in the limestone. The soil arches between the rock then collapses due to loading of the surface by ponded water or vibration of the surface.

3 GEOPHYSICAL INVESTIGATION TECHNIQUES

3.1 *GPR methodology and equipment*

GPR is a geophysical technique that allows rapid screening of large areas to be undertaken and is based on the transmission and reflection of high frequency electromagnetic pulses. Reflections of the transmitted GPR pulse occur at subsurface interfaces with contrasting electrical properties (dielectric and conductivity) such as the boundary between sand, soil and bedrock. Reflections can also be received from other subsurface features such as tree roots, boulders, buried services such as pipes and cables, and from nearby features above ground such as trees and aircraft hangars and experienced interpreters are required to correctly identify these during post processing.

GPR testing was undertaken with a MALA 80MHz shielded antenna interfaced to Mala X3M RAMAC control unit and a XV Monitor for real time display of data. Reflex software was used to digitally record the GPR data along with positioning from a Trimble Global Navigation Satellite System (GNSS) system. The 80MHz antenna was chosen as the most effective frequency of operation as it provides information up to 8-10m depth below the ground surface and is best suited for identifying deeper features. The GPR unit was towed behind an all-terrain vehicle at a target speed of 4km/hr with the predefined lines navigated using Chesapeake navigation software inter-faced to a tablet computer and GNSS. Figure 5 shows the GPR field setup and Figure 4 shows the GPR trackplot coverage over the site.

Figure 4 – GPR Field Setup showing towed 80MHz shielded antenna behind the all-terrain vehicle.

Figure 5 – GPR trackplot coverage

3.2 *GPR test site for calibration of GPR Interpretation*

A test GPR site was investigated at the nearby Cutta Cutta cave site to determine the effectiveness of the system to detect caves and assess the GPR signal response from an air-filled void beneath the surface. The GPR system traversed directly over a known cave and the record of this is shown in Figure 6. The signal response from the GPR presents a broad hyperbola feature on the record and effectively detects the presence of the known cave at the test site.

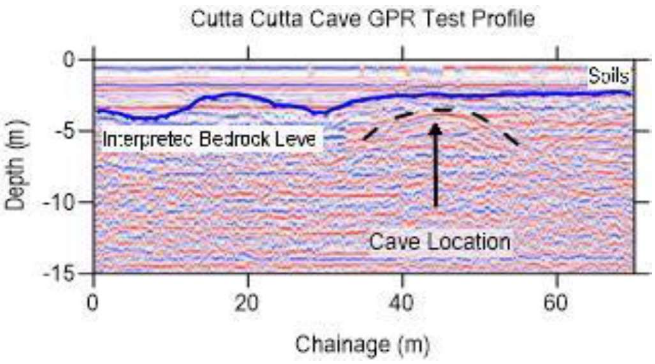

Figure 6 – GPR test site record

3.3 *GPR interpretation and development of ground model*

The transmitted (and reflected) GPR pulse is a wavelet containing a number of peaks and troughs. These peaks and troughs are represented on the GPR image as dark (high or positive) and light (low or negative) parallel "zones" or lines. The upper region of the GPR profiles shows the "primary pulse" (typically two dark parallel lines). This pulse is a combination of the direct wave from transmitter to receiver antenna and the reflection from the ground surface. Point source features such as metal grates or cables appear as narrow hyperbolic features on the GPR image. When the antenna approaches the buried feature the GPR signal reflected has a longer two-way travel time than when directly over the top and sometimes obscures features around these buried features.

The depths to the interpreted bedrock profile are calculated from the two-way travel time of the GPR signal in nanoseconds by applying a constant GPR pulse velocity of 0.141 metres per nanosecond (specific to the dielectric constant of material overlying bedrock). This velocity is typical for this type of material overlying the bedrock at the site and is calibrated at control points where test pits were undertaken.

The raw GPR data has been amplified with an exponential gain (increasing with increased time) to counteract the reduction in signal amplitude with distance travelled, to resolve subsurface features at depth.

The GPR interpretation involved replaying the GPR records and identifying and digitizing a bedrock reflector on the record as well as any localised features which could represent sinkhole structures within bedrock. Figure 7 presents a typical GPR record shown with the interpreted bedrock reflector.

These digitised depths to bedrock and associated X and Y positions provided by the GNSS allow a con-tour plan to be generated. The bedrock contour plan is presented in Figure 8.

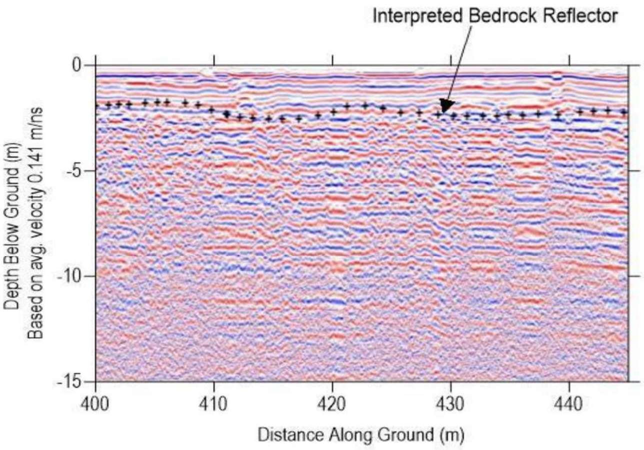

Figure 7 – GPR record with interpreted bedrock reflector

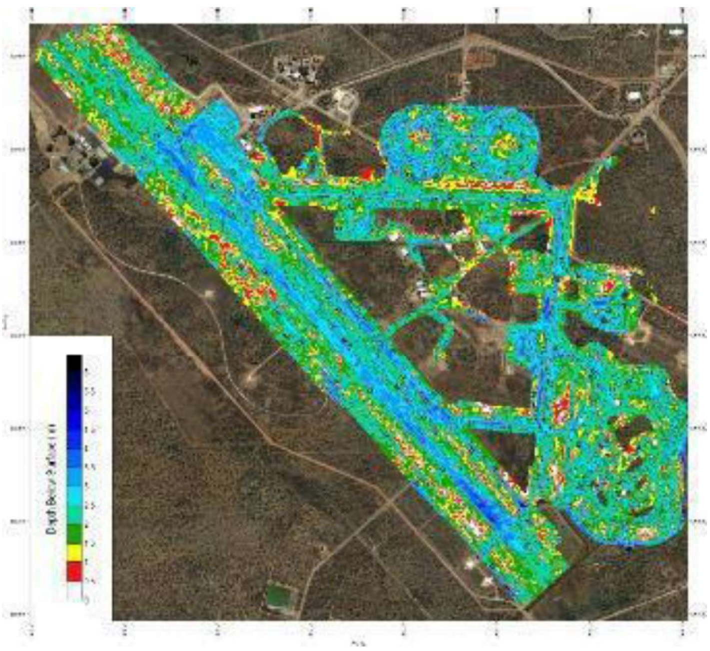
Figure 8 – Depth to bedrock contour plan.

In addition to the GPR data acquisition, surface features were also mapped as the survey was underway to identify any surface expressions that may assist the GPR interpretation and overall appreciation of site conditions. Three differing surface conditions were mapped over the site and these are zones of outcropping rock, depressions at the surface and small diameter sinkholes. The distribution of these is shown in Figure 9 with an observed sinkhole feature shown in Figure 10.

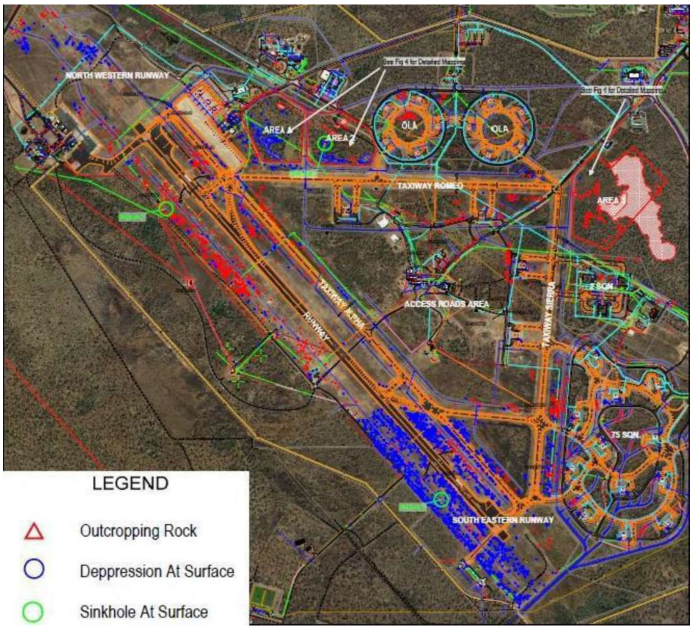

Figure 9 Distribution of observed surface features

Figure 10 Observed sinkhole feature (Diameter approximately 0.4m)

3.4 *Assessing GPR and surface observations for targeted further investigation*

Forty preliminary GPR targets were identified as potential areas of interest where features within the subsurface could represent sinkholes or near surface cavities. These preliminary targets were projected onto the services plan provided by the Client and were assessed to determine whether subsurface features identified coincided with buried services such as electrical cable conduits and stormwater pipelines. Most of these targets coincided with services and deep trenches associated with them and the shortlist of targets was reduced to thirteen.

At these thirteen target sites the seismic refraction technique was used to test the GPR interpretation and features identified which could be related to sink-holes, solution channels or shallow voids / caves. This technique uses the refraction of waves through the earth to generate a seismic velocity model which can be used to assess the density of subsurface materials. Detection of low velocity zones within the bed-rock would be indicative of voids in a karst environment.

An example of a GPR record and the corresponding seismic refraction testing model undertaken at one of these test sites is shown in Figure 11. The target located with the GPR shows a narrow depression feature on the bedrock which could be related to a sink-hole or slumping of material within zone. The seis-mic refraction model has identified a sharp lateral change in seismic velocities over this zone and agreed well with the GPR interpretation and has and was recommended for further direct testing.

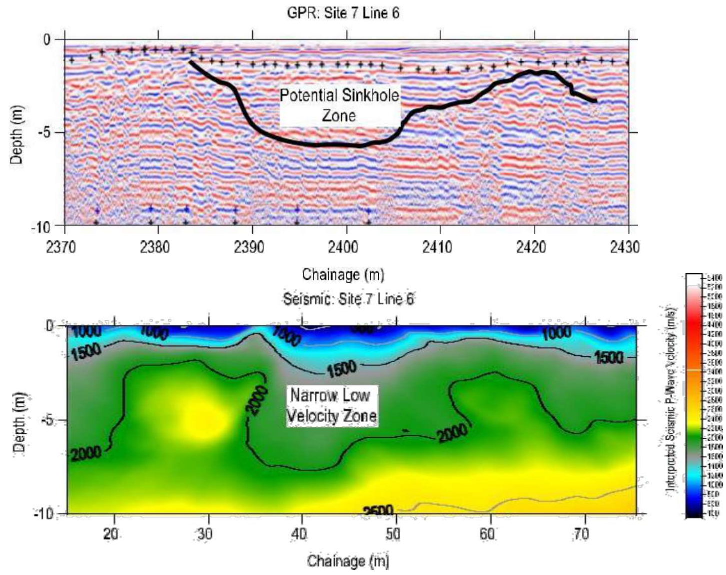

Figure 11 GPR target and seismic refraction testing model

4 CONCLUSION

This paper demonstrates the effectiveness of the GPR technique to screen large areas cost effectively and to identify subsurface structures that could be related to sinkholes and structures related to sinkholes. Coupled with other cost effective non-intrusive techniques such as detailed surface mapping observations whilst GPR data acquisition is underway, and targeting potential sinkhole structures identified with seismic refraction, a detailed surface and subsurface model of sites can be achieved and allows an informed geotechnical risk assessment to be undertaken.

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