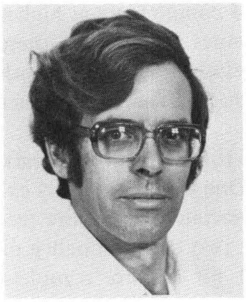

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Geophysical investigations of dolines* in lateritic terrain

J. E. Haigh and R. G. Nelson

Introduction

The detection of cavities in the near ground surface assumes vital enconomic significance when the area is subject to major engineering construction. Such is the case where the route of the proposed Alice Springs to Darwin railway crosses the Wiso Basin, between Tennant Creek and Katherine. Although the presence of dolines in the Wiso Basin was well documented, the overnight collapse of the Buchanan Highway into a sinkhole in 1982 highlighted the potential danger and dictated a full scale investigation.

Regional geology

The Wiso Basin formed during the Early Cambrian, with deposition of the Antrim Plateau Volcanics in a shallow marine environment, on a flat eroded surface of Proterozoic rocks. The volcanic activity was followed by Middle Cambrian deposition of the Tindall and Montenjinnie Limestones, which reach a thickness of 150 m in the area of interest. The next recorded deposition is that of the Cretaceous Mullaman beds, a sequence of quartz sands and silts bonded by clay cement, which were deposited in shallow lacustrine and marine conditions. The beds reach a thickness of 100 m and are characterized by strong lateral facies changes. During preliminary drilling, free-flowing sands, and clay-filled voids were encountered.

It has not been positively established, but it is presumed that erosion and karstic topography development occurred between the Cambrian and Cretaceous. Extensive weathering during the Tertiary resulted in laterite formation and strong preferential weathering along vertical joints. The Quaternary is represented by minor alluvial and aeolian sediments.

Doline distribution

Photo-interpretation infers that regional and local geological conditions exert some control on doline formation. An observed correlation of doline locations with lineation patterns and centres of drainage, implies that the regional fracture system has exerted significant control.

The stratigraphic juxtaposition of the Mullaman Beds and the karstic Cambrian limestone suggests an obvious mechanism for formation of dolines in the Mullaman Beds; by

Fig 1 Dolines on the Buchanan Highway formed late wet season, 1982 (courtesy of Dr R. W. Twidale).

* The generic term 'doline' is defined to include: broad, shallow depressions; deep, steep-sided sinkholes; piping structures or cavities which may lead to sinkhole formation (Fig. 1).

the collapse of those sediments into existing caverns in the underlying limestone. This concept governed the planning of initial geophysical testing, which was directed towards open cavity detection.

However, closer study revealed a more complex situation. It is important to note that the majority of sinkholes occur in the highly siliceous and strongly dispersive Mullaman Beds, and are surprisingly uniform in size, notwithstanding variation in the thickness of the beds. If collapse into limestone caverns were the major mechanism, it is expected that the size of the surface sinkhole would change with the thickness of the beds.

The primary mode of formation is now considered to be solution of silica from the Mullaman Beds, leaving a mesh of non cohesive clays supporting the surface soil. This leach zone slowly enlarges downward, until it reaches a highly permeable aquifer assumed to be at a depth of about 30 m. Flushing of the clays into the aquifer occurs during the next wet season, leaving the surface soil unsupported, and leading to sudden collapse. At all stages of development, it is anticipated that the doline will contain substantial accumulated clay-rich material.

It is of course quite probable that palaeo-karst topography will be strongly correlated with centres of doline formation, by encouraging the necessary downward flow of groundwater, carrying dissolved solubles.

Definition of geophysical targets

Based on the proposed leach-down hypothesis for doline formation, the expected properties of a doline-prone area will be:

REGIONAL

A strong association with faults and fracture zones, and with current or palaeo-drainage systems, or with underlying karst development.

LOCAL

Differential weathering and lateral facies variations, with vertical joints and both major and minor voids. A higher clay content relative to the surrounding zones. Occasional large cavities either within the limestones or the siltstones. Subject to seasonal variation, these may be either air or water filled.

Expected geophysical responses

The physical properties of the above areas would be expected to produce changes in the density, electrical conductivity and elastic constants of the medium, and the methods used to investigate the zone will depend on the resolution required, the depth penetration, and the cost and speed of the field method.

The methods used initially were dictated, to a large extent, by the adopted conceptual model of a simple 'hole in the ground'. Investigations were carried out using microgravity, seismic fan shooting, dipole–dipole resistivity, pole–dipole resistivity, shallow EM (EM31), ground radar, and high resolution reflection seismic surveys.

No definitively successful method was apparent, and investigation using Sirotem and refraction seismic methods was considered. Intuitively, the 'hole in the ground' model is a poor target for TEM, particularly if air-filled, because the diffusion velocity through the target will be near the velocity of light.

However, it is an observed fact that while TEM is unable to define the parameters of such high resistivity zones, the position of the interface with a conductive zone is well bounded, and thus the edge of the doline might generate a discernible response. Numerical modelling procedures are not suitable for this application and an orientation survey was planned in conjunction with a high resolution seismic refraction survey at two test locations.

The first area, Natural Well, was regarded as the definitive model for the proposed sinkhole target, while the second, Western Creek, was designed to follow up anomalous responses detected using ground radar.

After analysis of these surveys, further test work was carried out in the Natural Well area, and in the sinkhole area on the Buchanan Highway.

During later production survey along the proposed rail centre line, some 40 km of centreline were surveyed.

Natural well test site

The initial seismic work was carried out in the dry season, and aimed to produce seismic reflection sections to profile the top of the limestone. In general, the acoustic impedance contrast between the limestone and the overlying siltstone is large. However, the tenuous continuity of the interface reflector, suggests that it is rugose, or laterally inhomogeneous, which is consistent with the hypothesis of a karst topography.

The most significant feature of the data is a zone of delayed travel times and reduced signal amplitudes associated with Natural Well. An additional effect, caused by resonance of the cavity in response to seismic excitation, produces a separate peak in the power spectrum plot at about 100 Hz. This is consistent with the equation for a cylindrical cavity in a homogeneous medium (Biot 1952):

$$f = V/1.55D$$

f = resonant frequency
V = shear velocity
D = diameter of cavity

giving a diameter of 6 m for Natural Well.

A survey during the wet season, when the Well was full of water, was carried out to determine the effect on the P wave absorption. As anticipated, P wave absorption was considerably reduced. S wave measurements using horizontally polarised (SH) waves confirmed that the SH waves showed anomalous attenuation and delayed travel times. Comparison of the SH records with the conventional records, enabled identification of the SV arrival in the conventional records and permitted generation of shear-to-compressional velocity profiles. The attenuation of the SV wave is more pronounced and consistent over the cavity than the P wave travelling through the water-saturated zone.

For the Sirotem survey, it was felt that a very detailed 'Turam mode' survey would be most effective in detecting a small anomaly at the doline wall. The survey was conducted with a 200 m by 100 m loop, 50 m from the sinkhole, and traverses were surveyed on an existing 100 m by 100 m grid pegged at 5 m intervals, using a three component RVR receiver.

The vertical component and X horizontal (parallel to traverse) component showed no discernible response from the sinkhole, while the Y component showed only the anticipated random responses due to finite orientation accuracy.

Single turn 25 m coincident loop data showed responses which appeared to correlate with the sinkhole, but the data was compromised by a suspected instrument fault, and very low signal levels.

Western Creek test site

The primary purpose of this test site was to evaluate ground radar anomalies. Coincident loop (25 m and 100 m) and Turam mode surveys failed to give any discernible response in three different areas. The observed earth resistivity, from the Sirotem, was 50 Ωm, which predicted only a few centimetres penetration at radar frequency, and the validity of the radar response was questioned. Specific queries to the field personnel present on the radar survey, elicited the information that the radar anomalies were not repeatable. Further Sirotem tests in this area were abandoned.

At an area nearby, major sinkhole development was apparent, and the test survey was transferred to that site. A Turam mode survey confirmed that this configuration did not give discernible response, but a coincident loop survey gave a weak but definite conductive anomaly coinciding with the sinkhole.

The results from this survey suggested that the target zones were more realistically represented by a conductive source within a less conductive host. This empirical observation was rationalized by assuming that the target was in fact conductive clays either filling or lining the inferred doline.

Buchanan Highway test site

On the Buchanan Highway, a major zone of doline formation exists about 60 km west from the Stuart Highway. This area was chosen an an appropriate test site to evaluate a proposed survey methodology using Sirotem with follow-up refraction seismic work.

The seismic work was directed towards generation of constant offset panels to highlight anomalous attenuation and travel time delay effects. In general, the attenuation effects seem to be a better guide to anomalous ground conditions, as the associated travel time delays are basically short wavelength residual static variations, superimposed on broader regional variations in weathering thickness.

Using Sirotem, the area was surveyed with 100 m coincident loops, which extended across the doline area, and well into the surrounding countryside. The results confirmed that the background resistivity was uniform and about 50 Ωm. By contrast the resistivities in the area of doline formation were lower (6–20 Ωm), and characterized by rapid variations.

Comparisons of coincident loop and in-loop (RVR) data demonstrated that there was no discernible SPM (Super-Para-Magnetic) effects.

A detailed survey was conducted using 25 m coincident loops, using four turns to improve signal strength. This survey highlighted the resistivity contrast over the dolines, and also defined an area under the Buchanan Highway diversion, where the small but strong Sirotem response coincided with anomalous seismic responses.

This anomaly was selected as an appropriate drilling target to test the application of the method.

Unfortunately, because of the intricacies of corporate planning, the drilling was not carried out, and the subsequent production survey work had to be conducted using the unproven survey methodology.

Production survey work

Some 40 km of the proposed centre-line of the rail corridor was surveyed, in four different areas. Some sections were monotonously uniform in resistivity and are presumed to be at low risk from doline formation. However, in other areas, significant anomalies were detected, which are presumed to represent doline or potential doline formation.

Six different drill sites have been proposed to test different classes of Sirotem and seismic anomalies, but at the time of writing, this drilling has not been carried out.

Response of small multi-turn loops

An interesting observation from this survey is the response of small multi-turn coincident loops. It is an observable fact that increasing the number of turns on a 25 m loop gives an increase in signal strength much greater than that predicted by theory. The observed empirical relation is that for the 25 m loop, the increase is more nearly proportional to turns squared (i.e. a four turn 25 m loop gives the same received signal as a single turn 100 m loop). This phenomenon is still under investigation, but in the interim, the empirical relationship has been used in resistivity computations for the 25 m loop.

Acknowledgments

The work presented here describes only a portion of a total integrated investigation, and draws heavily on work carried out by members of the Northern Territory Department of Minerals and Energy Railway Investigation Unit, who have provided valuable assistance and discussion.

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