Integrated geophysical surveys applied to karstic studies

Rob McDonald, TerraDat (UK)* and Rob Davies, TerraDat (AUS) show how the use of a combination of non-invasive geophysical techniques can improve the reliability of near surface survey modelling

The investigation of features associated with karst environments is an important application of non-invasive geophysical methods. Although the physical principles underlying individual methods are well established, the merits of integrating different techniques in order to reduce model ambiguity are explored. We present case histories that illustrate how combinations of gravity, resistivity tomography and seismic refraction surveys enable improved model reliability of structures that would not generally be resolved by single-discipline approaches.

Microgravity methods in particular are generally employed to identify karstic features relevant to engineering work. While localised gravity 'low' anomalies are indicative of mass deficiency in the sub-surface we show that it is essential to carry out follow-up targeted seismic and/or resistivity tomography surveys to establish whether the anomaly is caused by a rockhead depression/sinkhole or by a sub-rockhead cavity. In addition, seismic surveys are shown to be useful for resolving ambiguities while interpreting drilling results from a targeted solution feature.

Introduction

Of the various methods that have been applied to the investigation of limestone solution features several have provided notable successes and are now routinely in use, i.e., resistivity tomography, microgravity, electromagnetic ground conductivity mapping and ground radar. Limestone environments tend to provide favourable conditions for the use of geophysical methods because there are relatively few material types present and they have very distinct physical properties. Limestone is very dense and very resistive to the flow of electricity, typical clay infill has a lower density but conducts electricity very well, and air voids have zero density and block the passage of electricity.

It is through combination of the survey methods that the nature of identified anomalous ground conditions can be interpreted, e.g., an area of anomalous low density may be due to the presence of an isolated air-filled void or a larger zone of clay filled fractures - this ambiguity can be resolved by resistivity tomography which would display anomalous high or low resistivities respectively.

Ground radar is a method that can provide high resolution information about the subsurface but its successful use is highly site dependent. Clay materials at or near surface severely attenuate the radar signal which prevents sufficient depth penetration. Highly fractured or broken rock can produce too many reflecting signals which detriments reliable interpretation. Best results are achieved when the radar antenna can be placed directly onto the rock surface and moved steadily in short stepped increments along a particular traverse line. The presence of an irregular surface and scrub causes the antenna to lift off the rock causing a great reduction in data quality as much of the transmitted signal is reflected at the surface.

Resistivity has a longer history in mapping buried karstic features than any other geophysical method. It offers advantages of cost, speed of acquisition and ease of processing over gravity measurements. Recent advances in acquisition have resulted from computer-controlled multichannel meters and have been complimented by vast improvements in interpretation software (e.g. Loke, 1996). The presence of infill sediments or water greatly improves the detectability of solution features due to the enhanced local conductivity within more resistive host limestone bedrock. The theoretical resolution limitations that affect the use of resistivity may be reduced in some instances by more dominant secondary effects such as drying-out halos and fracturing associated with the voids which could produce measurable anomalies due to the greater volume of affected material.

Theoretically the sensitivity of resistivity measurements increases with decreasing potential electrode separation and so the optimum array for mapping buried voids is the pole-dipole array (Lowry and Shive, 1990). However, practical considerations and processing techniques that iterate through model pseudo-sections leads us to favour the dipole-dipole array which also serves well for mapping the large horizontal boundaries associated with soil, rock and water table layers.

Microgravity surveys are widely employed for the detection of solution features and the increasing availability of high precision semi-automated instruments that can

**Ocean House, Hunter Street, Cardiff CF10 5FR, UK; E-mail; robmc@terradat.com*

read to accuracies better than 5 microgals has enabled targeting of relatively small features. It is vitally important that all corrections are applied to maintain the level of acquired data accuracy which includes removal of all local terrain effects which can often be more significant than measured anomalies where topography is irregular. Observation of a significant and localised gravity 'low' anomaly in a limestone terrain indicates the presence of solution features or a buried rockhead depression given that terrain effects have been reliably removed from the dataset. Where targeted seismic or resistivity tomography data show that there is no bedrock depression at the site of the gravity anomaly then the likely presence of a sub-rockhead solution feature has been identified. If the rockhead geometry derived from the follow-up resistivity and/or seismic data suggests a possible sinkhole then the gravity results can be modelled to determine whether there is evidence to suggest the presence of an underlying cavity.

Large sites requiring investigation can prove too laterally extensive for early use of combined resistivity and gravity methods. In such instances it is often useful to carry out a reconnaissance electromagnetic (ground conductivity) survey in an attempt to identify anomalous areas of the site to best target more detailed geophysical work. Various equipment and operational parameters can be set to investigate an appropriate depth range and features such as infilled sinkholes, cavities and fractures may cause measurable anomalies depending on the local conditions, depth of burial etc. While it could not be guaranteed or expected that all features would be identified using such a rapid reconnaissance approach it is often possible to locate the most significant shallow structures which can help to identify potential problem areas and it is certainly more beneficial than a random scatter of boreholes which are typically very unlikely to hit isolated karstic features.

Seismic refraction methods can prove very useful for proving the presence and topography of rockhead. While resistivity tomography can often be used to map limestone rockhead as well as investigating sub-rockhead structures there are some instances where the electrical contrast between sediments and saturated/fractured bedrock containing sediment infill or conductive water can be insufficient for clear identification of rockhead. Seismic refraction methods provide a reliable means for profiling rockhead without significant ambiguity because the velocity of limestone bedrock is generally beyond that possible for even very compacted unconsolidated sediments. While seismic refraction is not best suited for investigating solution features within bedrock it can prove to be a very useful tool for solving the main potential ambiguity affecting gravity surveys, i.e., whether an anomaly is due to a sub-rockhead cavity or a localised undulation in bedrock topography.

Case examples

Geophysical Investigation in Eire

Results from a recent geophysical survey carried out in a limestone environment in Eire are presented here to illustrate the useful combination of resistivity tomography and microgravity techniques. The survey was carried out to target solution features and fracture zones that would represent preferential flow paths within bedrock. A representative selection of the results is shown in Figure 1. The high degree of correlation between the survey methods is evident and the position of anomalous bedrock structures would have been identified by both survey methods individually. However, while the individual methods enable location of

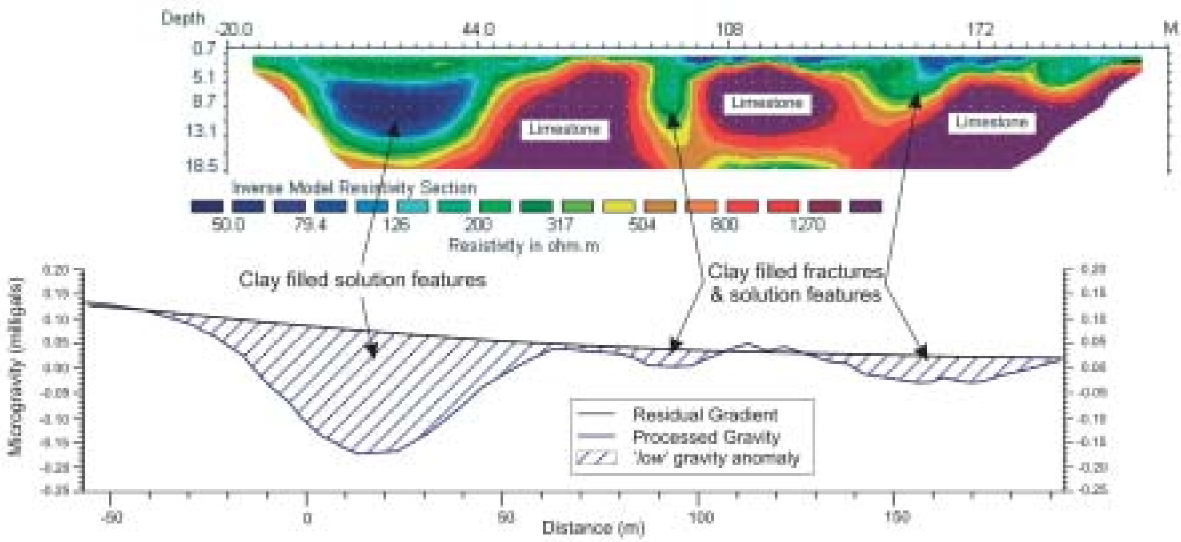

Figure 1

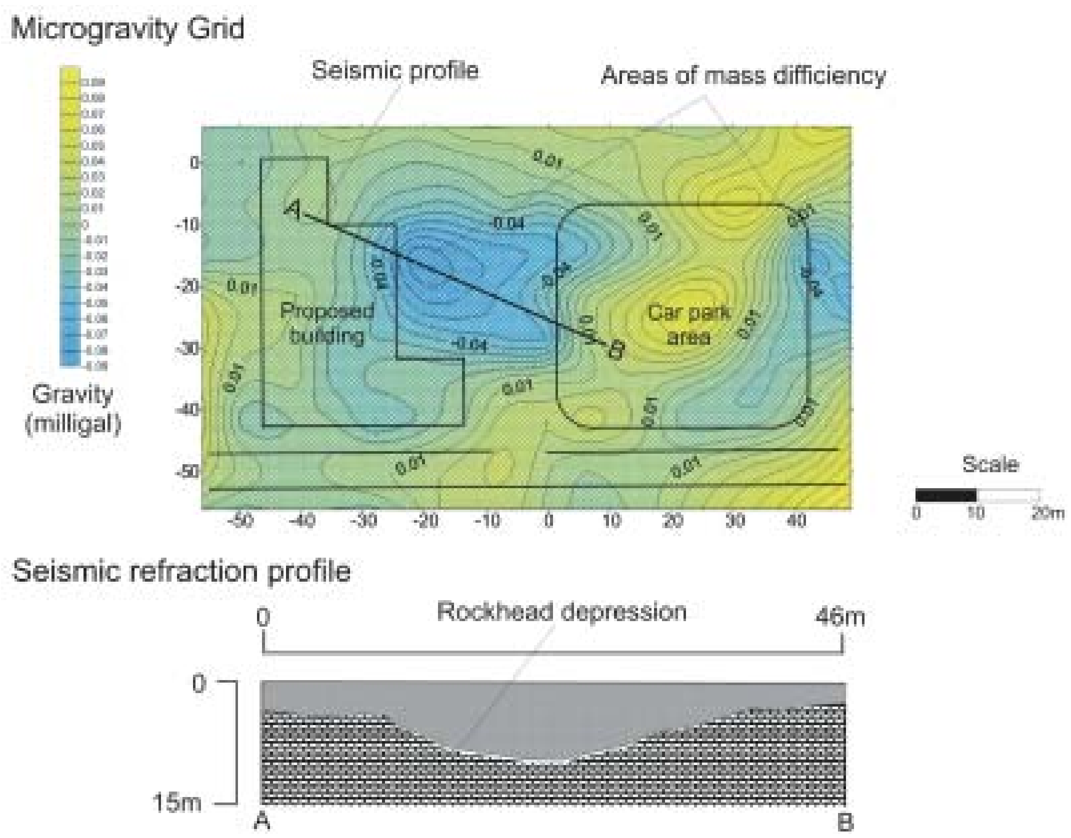

Figure 2

features, they do not enable certain identification of their physical nature for the following reasons: (i) the microgravity survey has identified the presence of localised mass deficiencies; but whether they are due to rockhead undulations or sub-rockhead solution features is not certain, and (ii) the resistivity tomography data reveals the presence and cross-sectional geometry of anomalously conductive zones within bedrock; but it is not certain whether they are due to local variations in permeability or due to solution of bedrock.

Correlation of the resistivity and gravity data enables examination of the physical characteristics of any identified anomalous features as well as providing geometrical control for modelling the gravity data. It is apparent from the results presented in Figure 1 that each of the main low resistivity anomalies is also associated with a mass deficiency identified by the gravity survey. If these low resistivity zones were caused by localised water ingress where there is no significant solution of bedrock, then there would be no associated negative gravity anomalies of the observed amplitude.

Given that an anomalous feature has been identified as being due to bedrock solution by reconnaissance geophysical work, it is then possible to carry out a more detailed investigation to attempt to constrain its physical characteristics in three dimensions. Orthogonal aligned resistivity traverses (or true 3D survey) can provide the geometrical constraint on gravity modelling necessary to enable reliable estimation of the density contrast of the solution feature with competent bedrock. An alternative approach would be to carry out a detailed gravity survey on a grid to enable calculation of the total mass deficiency and plan geometry of the solution feature or fracture zone. Incorporating the cross-sectional information derived from the original resistivity tomography data would again enable reliable calculation of the density contrast. The density contrast information could enable estimation of the void/bedrock ratio within the anomalous zone given assumptions about the likely infill material whether water, sediment or air. Evidence about likely infill material can be derived from knowledge of local water levels, sediment transport and from measured resistivity values and groundwater conductivities.

Geophysical survey at Pembroke Dock, Wales

Results from a geophysical survey carried out to target possible solution features beneath a developed site are presented in Figure 2. The case example was selected to illustrate the sometimes useful and often essential combination of a seismic refraction survey with microgravity data. A significant gravity anomaly was identified by the microgravity survey carried out over the development site. The thick surface asphalt cover and presence of underlying coarse grained fill materials made it difficult to carry out a resistivity tomography survey to investigate the large gravity anomaly. The asphalt renders it difficult to gain sufficient electrical contact between the electrodes and the subsurface, so the electrical contrast between limestone and coarse fill materials is not as clearly defined as the seismic contrast between loose materials and bedrock. Boreholes targeted on the gravity anomaly suggested that bedrock continued to depths in excess of 16 m and in nearby places only to 10 m. This implies that either some of the holes passed down through narrow voids/fractures or some of the holes hit large boulders at shallower depth. In order to resolve this apparent ambiguity a seismic survey was carried out across the main identified gravity anomaly. It revealed that average deepest bedrock depths are apparently about 10 m below surface and the conclusion was that some of the boreholes had indeed passed down through narrow local voids/fractures.

Conclusions

Geophysical methods offer a number of alternative approaches to the detection and mapping of buried karst features. A combination of two or more appropriate methods can enable derivation of a near complete solution with reduced requirement for follow-up invasive work. The combination of resistivity tomography and microgravity is a particularly powerful tool for targeting solution features and determining whether they are likely to comprise infilled or open voids. Resistivity tomography provides detailed cross-sectional information and can be acquired relatively rapidly along proposed road/pipeline routes or beneath proposed building foundations with microgravity data acquired along the survey line at the same time. The microgravity data is essential to establish whether low resistivity zones are caused by fractured rock or voids and whether anomalously high resistivity zones are caused by tight crystalline rock or air-filled voids. Without additional gravity data conclusive interpretation can be difficult, particularly in areas that have variable soil type and/or laterally varying rock type.

Microgravity can be efficiently employed as the primary tool of investigation usually where a small area is under investigation that does not extend in a particular direction. In this situation, it can prove inefficient to acquire multiple resistivity tomography or seismic refraction survey lines to cover the area and the methods are best targeted on observed gravity anomalies during follow-up work. Considering microgravity data alone, it can prove difficult to determine the likely form and depth of the causative feature and therefore the follow-up surveys can prove essential for interpretation and reliable modelling of the gravity anomaly. Of common interest for construction or hazard assessment, seismic refraction or resistivity tomography surveys enable determination of whether a suspected solution feature revealed as a low gravity anomaly is a cave with a substantial rock roof or comprises a swallow hole or localised rockhead depression. Seismic refraction surveys are generally unable to map sub-rockhead solution features. However, the method provides a powerful means of accurately mapping soil depths which is particularly useful for input to the gravity modelling process in areas where the soil/rock density contrast is not expressed as a significant resistivity contrast.

References

Loke, M.H. and Barker, R.D. (1996) Rapid least-squares inversion of apparent resistivity pseudosections. *Geophysics*, **60,** 1682-1690.

Lowry, T and Shive, P.N. (1990) An evaluation of Bristow's method for the detection of subsurface cavities. *Geophysics*, **55,** 514-520.