Contribution of geophysical methods to karst-system exploration: an overview

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Abstract The karst environment is one of the most challenging in terms of groundwater, engineering and environmental issues. Geophysical methods can provide useful subsurface information in karst regions concerning, for instance, hazard estimation or groundwater exploration and vulnerability assessment. However, a karst area remains a very difficult environment for any geophysical exploration; selection of the best-suited geophysical method is not always straightforward, due to the highly variable and unpredictable target characteristics. The state of the art is presented, in terms of the contributions made by geophysical methods to karst-system exploration, based on extensive analysis of the published scientific results. This report is an overview and should be used as a preliminary methodological approach, rather than a guideline.

Keywords Karst · Geophysical methods · Overview

Introduction

Karst areas are characterised by a specific type of morphology that is formed in carbonate and evaporitic rocks, primarily by dissolution. The structure of karst systems is complex and the related functioning mechanism of aquifers can be highly heterogeneous (Mangin 1975; Bakalowicz 1995; Ford and Williams 2007; White 2007). Therefore, karst areas are the subject of many geomorphological, geological, hydrogeological, geotechnical, environmental, archaeological, etc. explorations. Typical geological, hydrogeological and geomorphological studies provide partial information on the degree of karstification development, but cannot determine the internal structure of the karst system. The knowledge of the geometry and the structure of the different parts of a karst system (epikarst, infiltration zones, karst conduits, cavities, etc.) involve many uncertainties because of the complex nature of karst systems. Furthermore, vulnerability mapping of karst aquifers is based on infiltration-property distribution over the catchment area of a karst system (e.g. thickness and internal structure, presence and type of overlying sediments). Infiltration can be slower and diffuse if overlying sediments cover the karst system or can be fast and concentrated in areas that lack overlying sediments through karst features such as swallow holes or dolines (Andreo et al. 2009; Daly et al. 2002; Davis et al. 2002; Dörfliger and Plagnes 2009; Kavouri et al. 2011; Ravbar and Goldscheider 2009; Zwahlen 2004).

However, suitable characterisation of heterogeneities in the karst environment is challenging for ground-based geophysical methods. Depending on climatic conditions, the drainage, saturation and physical or geochemical characteristics of the system can vary. Conduits, for instance, may or may not be water-saturated, and some parts of the network may either be filled with unconsolidated sediments or even be empty. This complexity produces multiple and time-variable geophysical signatures.

This report is a forward-looking evaluation of the surface-based geophysical methods applied to karst-system exploration. First it describes the most common issues in karst exploration. Second, for each issue, it provides an overview of the most relevant geophysical research studies published over the last 20 years in international journals. Some research results presented exclusively at national and international conferences have been excluded because they could not be accessed. Finally, it evaluates the adequacy of all surface-based geophysical methods used for karst-system exploration

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with respect to the most common of these issues. Proposals are given for future geophysical works in karst terrains.

Background: geophysical methods in karst-system investigation

Since the 1960s, geophysical methods have been applied in the investigation and evaluation of geotechnical problems related mainly to voids, sinkhole detection or epikarst structures. Until the early 1990s, only a few published studies were well documented. Electrical resistivity techniques were used in cave detection (Cook and Nostrand 1954; Vincenz 1968; Dutta et al. 1970; Greenfield 1979; Militzer et al. 1979; Smith 1986). Very few studies focused on the use of geophysical microgravimetric and gravity gradient techniques to target subsurface cavities and karst features (Colley 1963; Neumann 1965; Arzi 1975; Blizkovsky 1979; Butler 1984). Cook (1965) applied a seismic method to map underground cavities using reflection amplitudes. Kaspar and Pecen (1975) used an electromagnetic (EM) method for tracing karst features in eastern Slovakia by means of differences in electrical properties between limestone and karst features. Greenfield (1979) investigated several geophysical methods for the detection of voids, caves and hazards. Moore and Stewart (1983) used seismic refraction, electrical resistivity tomography (ERT) and microgravity to delineate zones of increased fracture density. Steeples et al. (1986) mapped salt-dissolution subsidence features in Kansas (USA) utilising the seismic reflection technique. Vogelsang (1987) tested EM methods to map karst features. The results of all these studies revealed the value and the potential of using geophysics for karst-system exploration.

Since the early 1990s, geophysical investigations in karst regions have increased rapidly due to technological developments, lower costs, simpler field procedures and more rapid inversion and interpretation of data. Moreover, delineation of subsurface cavities and abandoned tunnels using geophysical methods has gained wide interest because their discovery is relevant for environmental, engineering and even archaeological studies.

During the last few years, several studies were undertaken in order to provide guidelines for geophysical methods in karst system exploration. Benderitter (1997) was the first to attempt to evaluate the possibilities of using geophysics in karst systems. Doolittle and Collins (1998) compared EM methods with ground penetrating radar (GRP) techniques. Thomas and Roth (1999) presented a comparison study between 12 methods (including four geophysical techniques) for sinkhole and void detection in eastern Pennsylvania and north New Jersey in the USA. Hutchinson et al. (2002) provided a useful comparison of various geophysical approaches for void detection. Fauchard and Pothérat (2004) established a guide for air-filled cave detection using geophysical methods. Bechtel et al. (2007) described geophysical methods adapted to karst study in a general book on karst hydrogeology. Gutiérrez et al. (2008) presented an evaluation of geophysical methods for sinkhole detection in evaporate areas based on the general use of the geophysical methods for karst exploration proposed by Hoover (2003). Finally, every few years ASTM International (2006) provides a standard guide for selecting geophysical tools. A restraint part of this guidebook evaluates the geophysical tools used for karst-system exploration.

Karst systems: the main challenges

Taking into consideration the complexity of a karst system, the main challenges related to environmental, geotechnical and hydrogeological exploration of karst systems were identified. Although the list presented herein may be oversimplified, it is based on the most frequent issues geophysicists have reported in the literature.

At this point, it is important to mention the inconsistency in the use of terms for karst-feature description within the different studies included in this report. For instance, many authors using the term "void" in fact refer to sinkholes (collapse hazards with no water movement). To homogenise the terms used for this review, Field's (2002) lexicon of cave and karst terminology was employed. Accordingly, five main issues can be delineated.

The limits and extent of a karst system

The extent of the catchment area will provide the geometry and the volume of the karst reservoir. Consequently, an estimation of the available water resources can be provided. How can geophysics help define the boundaries of a karst system? For example, can geophysical methods define vertical or lateral limits of an outcropping karst system or of a sedimentary buried karst system? Is it possible to locate the karst substratum or the contact with other non-karst formations as well as the presence of faults?

Structural discontinuities

The presence of fractures as well as their orientation and intensity are important knowledge to decipher karst functioning because the drainage network of the karst system depends highly upon them. Combined with the hydraulic gradient, this information is very useful to evaluate the lateral underground flow and the vertical recharge. When epikarst is present, it constitutes a highly fractured zone above the massive carbonate rocks with high water-stock capacities. Can geophysical methods distinguish more fractured zones of a karst system from the massive part of the same formation? Can it define the orientation of the fractures?

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Preferential pathways and/or concentrated infiltration

Sinkholes are near-surface indicators of deep underground active karst features such as cavities, conduits and dissolution-enlarged fractures. Often, sinkholes are also points of recharge to the karst groundwater system and generally the most vulnerable points of a karst system. These features often do not have a surface expression, and their presence may go unrecorded. Can geophysical methods help localise such preferential pathways?

Cavities

Cavities dependent on their location inside the karst system (i.e. above or below the piezometric level) can be partially or entirely air- or water-filled.

Empty cavities

Locating cavities in the ground is an important task in drawing geohazard maps, particularly in populated areas. Detecting underground cavities beneath construction sites and urban areas is a key task for many engineering projects. Every year, subsidence and surface soil failure due to underground voids causes substantial damage around the world. In what conditions can geophysical methods help to localise air filled cavities?

Water-filled cavities

Cavities can be partially or completely water-filled and, depending on the composition of the water, can have a resulting electrical conductivity ranging from very conductive to relatively resistive, compared to host rock. In addition, water-filled karst conduits play a crucial role for water supply in many parts of the world. Can geophysical methods accurately provide the position, in three-dimensions (3D), of a water-filled cavity? What about clay-filled cavities?

Finally, sedimentary covering, when it exists, plays a very important role for karst hydrogeology, and its characteristics (thickness and consistency) can significantly change the geophysical response of the underlying karst-related target. Moreover, sedimentary covering of a karst system can often also be a specific target for geophysical investigation in order to evaluate vulnerability issues of the karst aquifer and to contribute towards a protection strategy.

Contribution of geophysical methods to karst-system exploration

Geophysical methods aim to characterise the variations of the physical parameters of underground formations. Geophysical measurements produce a set of data in which various parameters are measured (observed). Each of these parameters is related to one or more physical properties of the subsurface and to their spatial distribution. These methods are widely used for hydrogeological, environmental and engineering explorations throughout the world in various geological formations. However, geophysical methods are not systematically used for karst-system exploration.

In recent years, several geophysical methods and assessment techniques have been rapidly developed. In general, the investigation depth for karst exploration of the subsurface is between 2 and 200 m. For most studies, several methods are combined to compare the benefits of each method.

For an accurate presentation of the geophysical methods used, the terminology was standardised for the present report. For example, the term ERT is used even though in the original papers the authors employed several terms such as 'resistivity imaging', 'resistivity 2D profiling' (two-dimensional profiling), etc. In the following section, geophysical results will be listed according to the five main issues previously recognised and discussed. For all these studies, geophysical results provided information for more than one karst-related issue.

Limits and extent of a karst system

Lange (1999) mapped the karst structure and groundwater channels beneath sediments using three techniques: EM, gravity, and self-potential (SP). The EM method defined the boundary between carbonate rock and alluvium. Zhou et al. (2000) demonstrated the advantage of using resistivity methods, and mainly ERT, to define the depth to carbonate bedrock in sedimentary, shallow, covered karst terrains. Combining 2D ERT, seismic refraction and the high-resolution reflection seismic methods, Šumanovac and Weisser (2001) mapped the vertical boundaries of a karst system in Croatia. He et al. (2006) used integrated passive source EM and the controlled source audio magnetotelluric (CSAMT) method for mapping the deeply buried geological structures in karst terrains in China. Chalikakis (2006) used the time domain electromagnetic (TDEM) method to map covered deep karst in a sedimentary basin in north Peloponnisos in Greece. Mari et al. (2009), from a 3D seismic data set and wells, obtained a 3D porosity model of a near-surface karst aquifer. These results helped locate highly productive zones and could be useful for flow modelling.

Most of these published studies involved the upper limits of the karst systems under sedimentary covering. However, their results also provide important information concerning the thickness and the consistency of the overlying sediments.

Structural discontinuities

Grandjean and Gourry (1996) successfully used GPR data to obtain a 3D near-surface feature map in a marble quarry. Seismic reflection profiling was combined with microgravimetry and borehole data by Benson (1995) to identify karst near-surface highly fractured zones and to assess their impact upon a proposed bridge design in

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Florida (USA). Turberg and Barker (1996) used a combination of ERT and radio magnetotellurics—RMT, enhanced very low frequency resistivity mode (VLF-R)—to describe the near-surface epikarst zone on a test site in Switzerland. The seismic refraction method was employed to evaluate subsurface fracturing by Johnston and Carpenter (1998) above a coal-mine panel on the southern portion of the Illinois coal basin (USA). Busby (2000) tested the effectiveness of azimuthal apparent-resistivity measurements as a method for determining fracture strike orientations. Bosch and Müller (2001) developed and tested a very low frequency electromagnetic (VLF-EM) gradient technique to map near-surface heterogeneities in a karst area in Switzerland. A few years later, a comparison of the VLF-gradient array with ERT, RMT and continuous VLF-EM, methods was successfully carried out in the same area to identify and map karst near-surface heterogeneities also as the epikarst zone (Bosch and Müller 2005). Sheehan et al. (2005) examined and discussed three commercial refraction tomography codes with respect to karst applications. They demonstrated that refraction tomography can assess many of the 3D features observed in these environments such as epikarst, where fracture density is important. Elawadi et al. (2006) employed a combination of ERT with a dipole-dipole array, GPR and VLF-EM methods in southern Cairo, Egypt. Integrated interpretation led to the delineation of hazard zones that were rich with vertical and sub-vertical faults, fracture zones, and geological contacts. Rey (2007) successfully mapped the near-surface fracture density and extent of a karst system in southern France with the Slingram type EM method (EM-31 device). Time-lapse microgravity measurements have been carried out for over 40 sites in the Larzac karst plateau (southern France), complemented by absolute gravity measurements, by Jacob et al. (2008, 2009, 2010). These measurements provide valuable information about the water-storage temporal dynamics of the epikarst zone.

Preferential pathways and concentrated infiltration

Witten et al. (1997) noted that the broadband EM induction technique holds promise for the detection and location of underground structures in the Anacostia metro station, Washington (USA), and in Nye County, Nevada (USA). EM conductivity mapping was combined with gravity, GPR, seismic refraction and electrical sounding (ES) by Carpenter et al. (1998) to identify sinkholes in the Oak Ridge reservations in Tennessee (USA).

An integrated microgravity and ERT geophysical survey was successfully conducted by McGrath et al. (2002) to detect underground voids in south Wales (UK). The results were integrated in groundwater vulnerability mapping. Kaufmann and Quinif (2001) used an ERT system and cone penetration tests to delineate cover-collapse sinkhole areas. Batayneh et al. (2002) employed GPR to delineate buried sinkholes in the Dead Sea Basin in Jordan. That study tested the usefulness of GPR to identify and locate buried sinkholes as a means of interpreting the existence of these sub-surface hydraulically active karst features. Van Shoor (2002) demonstrated that ERT was a geophysical tool that was well suited for the detection and mapping of sinkholes in dolomitic areas. Moreover, Zhou et al. (2002) used and compared several ERT arrays in order to detect a cover-collapsed sinkhole in Maryland (USA); a mixed array was preferred. Ahmed and Carpenter (2003) combined electrical tomography and electromagnetic techniques to map high-conductivity anomalies linked to filled sinkholes in east-central Illinois (USA). Time-lapse microgravity was used by Branston and Styles (2003) to investigate and monitor sinkholes in England (UK). Ezersky et al. (2006) combined TDEM, GPR, ERT and magnetic methods to study sinkhole development in the Dead Sea area (Middle East). Jardani et al. (2006) developed SP tomography in order to detect cavities related to sinkholes. Vertical flow of water is necessary for this method. A year later, preferential infiltration pathways were detected with joint inversion of SP and Slingram EM source (EM-34 device) conductivity data (Jardani et al. 2007). ES and hydrogeological investigations were carried out to characterise an unusual, from the hydrogeological point of view, epikarst in southern Italy by Petrella et al. (2007). Because of the high fracture density and good interconnection of openings within the underlying limestone, the percolation water was found to be diffused below the epikarst zone also. Kruse et al. (2006) successfully used GPR and ERT to map a large developing sinkhole in a covered karst terrain in west-central Florida (USA). Pueyo-Anchuela et al. (2009a, b) employed GPR to characterise processes involved in karst hazards and they propose a number of associated geomorphologic sections. Geomorphologic interpretations were also made from ERT and seismic refraction tomography data in karst depressions by Siart et al. (2009). Valois et al. (2010, 2011) combined Slingram, ERT and seismic refraction methods to identify buried or hidden preferential pathways, characterize dolines geometry and provide information about doline fillings.

Cavities

The drainage phenomena of karst systems are related to generally irregular cavities, fractures and fault zones, which decrease seismic velocities. In spite of successful case histories, void detection is still a challenge because of the lack of a standard, quantitative void-detection technique. In addition, existing nondestructive techniques do not consider the effect of lateral inhomogeneities, i.e. cavities, in the wave propagation. Thus, the detection of underground cavities needs further study.

Detection of cavities seems to be the most popular target for geophysical methods. The rock surrounding natural cavities is often disturbed, particularly in carbonate karst environments where a cave is formed by the chemical and physical interaction of groundwater with the rock. In such an environment, fractures and the dissolution of rock surrounding a karst cavity creates a larger bulk anomalous volume than the cave itself. Fortunately, this helps geophysical methods detect such

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caves more easily. Also the air-filled cavities have a near-infinite electrical resistance compared to the damp limestone and readily produce recognisable anomalies. However, their detection is controlled by the volume and the depth of the cave. Consequently, it was found that the effective geophysical size of each cavity varies with the geologic environment, but it is usually larger than the true size of the cavity. A variety of geophysical techniques can be used to detect the presence of caves and voids below the surface. All of them are based on a physical contrast between the cave or the conduit and the surrounding rocks.

Air-filled cavities

The resistivity of air-filled caves is always significantly higher than the bulk rock. Ogilvy et al. (1991) managed to detect air-filled cavities using the VLF resistivity method and Noel and Xu (1992) experimented with ERT for cave detection. Camacho et al. (1994) developed a gravimetric 3D inversion approach to detect air-filled cavities. Robert and de Bosset (1994) successfully conducted experiments in laboratory concrete structures for cavity detection with GPR. Guérin and Benderitter (1995) explored a near-surface karst system using a combination of VLF resistivity and electrical methods. McMechan et al. (1998) tested GPR to map cavities in a paleokarst system in Texas (USA). Cavity detection within other similar geophysical targets, by combining refracted and diffracted seismic waves, was demonstrated by Belfer et al. (1998). Batayneh et al. (1999) and Batayneh and Al-Zoubi (2000) presented ERT results for cave detection inside salt formations in Jordan. Gautam et al. (2000) attempted to map subsurface cavities by combining electrical sounding (ES) and electrical profiling (EP) and gamma ray measurements. Leparoux et al. (2000) demonstrated the potential of the seismic Rayleigh wave method for cavity detection and Chamberlain et al. (2000) successfully used GPR to delineate karst cavities. Several years later, Leparoux and Grandjean (2004) compared several seismic techniques for cavity detection at an experimental test site.

Beres et al. (2001) combined GPR and microgravimetric methods to map shallow subsurface cavities in western Switzerland. Rybacov et al. (2001) used microgravity to detect and monitor cavities in the Dead Sea area. Gibson et al. (2004) used ERT to locate an unknown 210-m-long, 70-m-wide and 25-m-deep collapse feature in eastern Ireland beneath sediments. A magnetic investigation of an unfilled paleokarst collapse structure produced a 40-nT (nano Tesla) anomaly, illustrating that the technique can be employed in Ireland to locate unknown caves. El-Qady et al. (2005) combined ERT using a dipole-dipole array and GPR to the east of Kattamya at Al-Amal Town, Cairo, to image shallow subsurface cavities. Three-dimensional interpretations of GPR have been used to identify burials and other archaeological features. Nasseri-Moghaddam et al. (2005) used the multi-channel analysis of surface waves (MASW) and presented the results of computer simulations of surface-wave propagation for a homogeneous medium containing a void. The numerical results of this study do not include other situations that may be encountered in natural settings such as inclined layers, reflecting boundaries and 3D conditions. Thierry et al. (2005) and Debeglia et al. (2006) took microgravity measurements in conjunction with MASW to detect and characterise karst structures in an urban environment, in Orléans (France). Kofman et al. (2006) demonstrated the value of reverberation phenomena in GPR records to detect near-surface air-filled cavities. Detecting air-filled cavities, within other geophysical targets, with P-wave seismic tomography was demonstrated by Grandjean (2006). Cardarelli et al. (2006) successfully mapped buried cavities with ERT under the city of Rome (Italy) and Piscitelli et al. (2007) used a combination of GPR and microwave tomography to detect shallow cavities in an archaeological site in southern Italy. Gravimetric, magnetic and GPR surveys led to successful detection of karst cavities in the Zaragoza area in north-eastern Spain (Mochales et al. 2008).

Water-filled cavities

Holub and Dumitresku (1994) conducted pioneering experiments for water-filled cavity detection using GPR and ERT methods. Zhou et al. (1999) found evidence of a water-filled conduit using the SP method. The absence of electrically conductive sediments at the surface allowed Al-Fares et al. (2002) to detect a known partially water-filled cavity 20 m deep at the Lamalou site in southern France with GPR. At the same site, Vouillamoz et al. (2003) combined magnetic resonance sounding (MRS) and ERT to map the partially water-filled cave. MRS proved to be a useful tool for water-filled conduits as soon as the quantity of water was sufficient to be detected. A new methodology for MRS data acquisition and interpretation was developed for locating water-filled karst cavities (Boucher et al. 2006). This methodology was used to investigate a wide, shallow, water-filled conduit in the Ouysse karst system in the Poumeyssens shaft (France). A 2D numerical MRS response model was designed to improve accuracy over the previous 1D MRS approach. In a further improvement, Girard et al. (2007) made use of magnetic resonance tomography (MRT). This work emphasises the gain in resolution for 2D and 3D imagery of MRT versus the interpolation of 1D inversion MRS results along the same profile. Numerical modelling results show that the MRT response is sensitive to the size and location of the 2D target in the subsurface. For the same test site in the Poumeyssen shaft, Guérin et al. (2009) demonstrated the efficiency of combining MRS, ERT, mise-à-la-masse and seismic methods to accurately characterise the shallow water-filled conduit.

Legchenko et al. (2008a) applied the MRS method to estimate the volume of a water-filled cave formed by salt dissolution in the Nahal-Hever area of the Dead Sea coastline. A quantitative verification of the accuracy of karst-volume estimates in Nahal Hever with MRS was not possible, but in a qualitative sense MRS results are found to be in good agreement with all other available data.

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Numerical modelling of the accuracy of the 1D MRS estimation of different 3D-target volumes (Legchenko et al. 2008b) shows that, under Nahal Hever conditions, this type of volume can be estimated. The results of this field study can help to estimate the risk of the development of new sinkholes related to water-filled cavities.

Overview of the geophysical results

The geophysical response depends on the size of the target in relation to its depth and on the contrast between the physical properties of the target and the surrounding rock. The size of karst features is usually small, except for caves, which have a larger size but are often located at greater depth. The amplitude of geophysical anomalies is, moreover, an inverse function of the distance between the measurement point and the structure. In addition, the lateral limits of geophysical methods are linked to the measurement sampling (investigation step) and the vertical limits correspond to the investigation depth, which is also related to the equipment, configuration array and the physical properties of the carbonate matrix.

It is important to point out that the goal of this present report was not to review all the previously described scientific publications but mainly to collect the geophysical studies, standardize the main karst issues and summarize the usefulness of all available surface-based geophysical methods. Methodology and results are considered of a good quality and their publication in high-standard scientific magazines is the guarantee of this statement. However, studies cannot be compared or criticised because, firstly, the different investigated karst systems were highly variable from the geological and hydrogeological point of view and, secondly, all geophysical methods are in constant development. Certainly some studies were undertaken several years before the methods could provide better results with the use of new equipment or inversion software.

Electrical methods

Conventional resistivity techniques (ES and EP) cannot give satisfactory results in areas with very complex subsurface geology such as karst areas. One of the theoretical assumptions for ES is a horizontal stratified earth model, which is rare in karst areas. However these techniques can be used for exploration of the limits of buried karst under sedimentary covering. The use of the mise-à-la-masse method should give indications on water-filled cavity orientation, as it does with conductive bodies in mining exploration. The use of 2D and 3D ERT has considerably increased in the last 10 years. Resistivities increase if the karst features are filled with air and decrease if they are filled with clay and/or water. The presence of clay generally decreases resistivities more than water (valid for fresh water, but not for salt water). In real exploration, their influence cannot be determined because of the unknown and irregular shape of the features and the fact that the degree of the filling is unknown most of the time. Electrical resistivity methods can, in any case, give more information on the lithology of the host rock because they engage the entire rock mass, but some structural features can be resolved by using 3D electrical tomography (even if such measurements are rare), which is sensitive to rock discontinuities. However, for all resistivity methods, how to implement the electrodes properly in the ground and secure adequate contact remains a major practical issue to be resolved. This can be extremely difficult for outcropping limestone, for instance.

The SP technique seems to be a suitable low-cost geophysical tool to detect preferential pathways when water flow is included. New algorithms are being developed to improve the accuracy of the technique. Although electrofiltration is a very attractive phenomenon to track the flow of water in water-filled cavities, most often signals recorded with SP measurements on such structures do not have only one source (i.e. telluric currents due to induction of ionosphere and electromagnetic storms, bioelectric effect of tree roots) and therefore cannot often get conclusive results on the water flow. In addition, electrofiltration is strongest for fluid flow in a permeable matrix.

Electromagnetic (EM) methods

Electromagnetic (EM) geophysical methods have proved useful in identifying and locating several karst features.

Slingram sources (EM at low induction number)

For the most part, two pieces of equipment have been used for the studies presented: the EM-31 and EM-34. Both can provide important information on the lateral variations of the near-surface karst features such as filled fractures and lateral contacts with other geological formations. While addressing the ground's electrical resistivity, these EM techniques provide light-weight equipment with high resolution and fast measurement progress, which is well appreciated mainly during preliminary geophysical studies.

Time domain electromagnetic (TDEM) and controlled source audio magnetotelluric (CSAMT) methods

These techniques have been used successfully only a few times, mainly to locate the upper part of a sedimentary-buried karst system and to characterize the overlying sedimentary covering. However, CSAMT can also be employed in an outcropping karst, where TDEM seems not to be working correctly.

Very low frequency (VLF) techniques

Enhanced VLF techniques (e.g. with broadened frequency range or continuous measuring capabilities) such as RMT (enhanced VLF-R), radiofrequency electromagnetics (RF-EM) and VLF gradient (both enhanced VLF techniques)

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have proved particularly useful for near-surface karst structure detection and imaging. Combined application provides quick detection of preferential vertical water flow paths as fractures, faults and sinkholes as well as the investigation of sediment-cover layer thickness. However, published case studies using enhanced VLF techniques have mainly been carried out with academic prototype equipment. Currently, there are only a few types of equipment commercially available. All these equipment types are using VLF and low frequency (30–300 kHz) radio transmitters, which are located at several positions around the world and are used principally for navigation and submarine communication. The frequency and the orientation of these transmitters play an important role in the geophysical surveys. Consequently another practical issue during a geophysical campaign that uses this type of equipment can be the reception of the appropriate radio transmitter towards the investigation depth and the orientation of the transmitters.

Ground penetrating radar

Ground penetrating radar (GPR) is very efficient for describing the epikarst in detail (i.e. the shallow part of karst systems) and the infiltration zone of karst aquifers, where limestone crops out at the surface. In recent years, GPR techniques appear to be the most popular geophysical tools for identifying and locating subsurface karst features such as cavities, conduits and solutionally enlarged fractures. GPR is extremely limited when the overburden is electrically conductive (as it commonly is in temperate lowland karst where there is a thick residual clay soil cover). The absence of electrically conducting sediments such as clays and the use of low frequencies (less than 100 MHz) make the application of GPR to limestone formations efficient and useful because of the weak attenuation of the radar waves.

Seismic methods

Structural information could be extracted from reflections in seismic data. Indeed, reflections help to determine vertical and sub-vertical boundaries such as faults and geologic contacts. Horizontal limits can be expected as well if there is a velocity contrast at the top or the bottom of the karst medium, for example. However, seismic reflections could be weak in karst terrains, due to uneven reflectors and a high level of noise such as when the refraction energy is dominant in recordings. Seismic refraction techniques can provide important knowledge of the near-surface karst heterogeneities such as preferential pathways and near-surface cavities. Nevertheless, the seismic velocity has to increase with depth for a sufficient investigation depth and a near-surface fast layer could hide underground structures.

The spectral analysis of surface wave (SASW) method has been used to assess near-surface soil conditions as well as to detect underground voids. Advancing the SASW method, the multi-channel analysis of the surface wave (MASW) method is based on the use of several transducers. The MASW method removes noise more effectively and identifies higher modes of Rayleigh waves better. MASW, sensitive to the soil stiffness profile, helps to reduce these ambiguities by characterising the mechanical behaviour of the gravity anomalous zones, and thereby minimising the extent and cost of mechanical controls.

Microgravity

Successful application of the gravity method for the detection of sinkholes depends on a density contrast between the material filling the sinkhole and its surroundings. Gravimetry requires high-density contrast between the cavity and the surrounding matrix. This method detects only large sinkholes or those located close to the ground surface but cannot be used to track the presence of buried sinkholes, because the presence of open conduits does not provide a strong perturbation of the gravity field. Microgravity, conducted with close spacing and careful implementation in order to ensure high resolution and accuracy, remains one of the methods best suited to the detection of voids in the uppermost 20 m, even when these voids are relatively small. Microgravity can also be accurate in delineating near-surface zones of increased fracture density and also in revealing major fractures with important gravity anomaly amplitude. The combination of microgravity with absolute gravity measurements seems promising in providing information at large lateral scales about water storage and the dynamics of the epikarst zone.

Magnetic resonance sounding

Magnetic resonance sounding (MRS) is a geophysical technique developed for groundwater exploration. This technique can be used for investigating karst aquifers. Generally, the study of a karst water-filled feature requires a 3D field setup and corresponding multichannel data-acquisition instruments. Now only single-channel MRS equipment is available; thus, the time needed for a 3D MRS field survey is multiplied by a factor of four or five. Moreover ambient EM noise greatly influences MRS measurements. At the current stage of instrument development, the method is limited to detecting large water-filled near-surface targets in areas with low ambient EM noise. Multi-channel data acquisition instruments and 2D and 3D numerical approaches seem promising for hydrogeological karst investigations.

Discussion

The adequacy of ground-based geophysical methods and their measuring techniques for the most common issues in karst formations are presented in Table 1. The notation—recommended (+++), appropriate but incomplete (++), appropriate but limited (+), and not recommended (0)—is based on the results of the previously described scientific

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Table 1 Adequacy of ground-based geophysics for karst-system exploration

Ground based geophysics		Adequacy of the method												Remarks	
		With sedimentary covering					Without sedimentary covering					Sedimentary covering			
Method	Measurement technique	Boundaries	Fractured zone	Preferential pathways	Cavities		Boundaries	Fractured zone	Preferential pathways	Cavities		Type	Thickness	Rent cost per week	Min number of operators
					Air-filled	Water-filled				Air-filled	Water-filled				
Electrical	ES	+++	++	+	0	0	+++	+	+	0	0	++	+++	II	3
	ERT	++	++	++	++	++	+++	++	++	+++	++	+++	++	III	2
	Mise-à-la-masse	0	0	++	0	++	0	+	++	0	++	0	0	II	2
	SP	0	++	+++	0	++	0	++	+++	0	++	+	0	I	2
EM	Slingram	++	++	++	+	+	++	++	++	++	++	+++	++	II	2
	TDEM	+++	+	0	0	0	+++	+	0	0	0	+++	+++	II	2
	GPR	0	+	+	+	+	+	+++	++	+++	++	+	0	II	3
	CSAMT	+++	++	++	+	+	+++	+++	++	+	+	+++	+++	IV	2
	VLF res.-RMT	++	++	++	+	+	+++	+++	+++	+	+	+++	+++	II	2
	VLF EM	+++	+++	+++	+	+	++	+++	+++	+	+	++	+	II	2
Seismic	Tomography	+++	++	++	++	++	+++	++	++	++	++	++	++	IV	2
	MASW	++	++	++	++	++	++	+++	++	++	++	++	++	IV	3
Microgravity	Profiling or mapping	0	++	+	+++	++	0	+	+	+++	++	0	0	III	2
Magnetic	Profiling or mapping	0	0	0	0	0	0	0	0	0	0	++	0	II	2
MRS	Sounding	0	0	0	0	+++	0	0	0	0	+++	+	0	V	2

+++ recommended; ++ appropriate but incomplete; + appropriate but limited; *0* not recommended

I <300 €; *II*301–600 €; *III*601–1000 €; *IV*1,001–2,000 €; *V*>2001 €—sources: ABEM France (2010), IRIS Instruments (2010), Expins (2010, Geomatrix (former Georental) (2010). Rental prices can vary depending on the geographical area, equipment type and model, time of rental etc.

CSAMT controlled source audio magnetotelluric; *EM* electromagnetic; *ERT* electrical resistivity tomography; *ES* electrical sounding; *GPR* ground penetrating radar; *MASW* multichannel analysis of surface waves; *MRS* magnetic resonance sounding; *RF-EM* radio frequency electromagnetic; *RMT* radio magnetotellurics (enhanced VLF-R); *SASW* spectral analysis of surface wave; *SP* self potential; *TDEM* time domain electromagnetic; *VLF* very low frequency; *VLF-R* very low frequency-resistivity

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studies. A method stands as: (1) *recommended* when, in many studies, results for the corresponding issue are relevant and even, in several cases, the method can stand alone to characterise the karst-specific target; (2) *appropriate but incomplete* when, for the specific karst issue, results are good but are mostly combined with other methods to provide concrete interpretation of the data; (3) *appropriate but limited* when only a few studies show the usefulness of the method even when combined with other methods; and (4) *not recommended* when the method is not adapted to the geometry and physical properties of the specific target. The optimum number of operators and weekly rental cost (rough value) of each one is also presented in Table 1.

However, it is important to remember that the response of each geophysical method is highly dependent on overburden sediments. Their thickness and consistency (percentage of clay, density, presence of water, etc.) can significantly change the geophysical signature of the target also as its depth is increasing. The presence, the thickness and the structure of the epikarst zone is also extremely important.

Table 1 presents the state of the art in terms of the contribution made by geophysical methods to karst-system exploration, based on published scientific results. It should be used as an overview and as a preliminary methodological approach rather than a guideline. For each karst-related issue, at least one geophysical method is recommended. However, the use of a combination of geophysical tools is always preferable to obtain a better-constrained model of karst features. Due to the specificities of each karst system, the suitability of each geophysical method can be site-related. Consequently preliminary experiments in the study area, before a survey, are highly recommended in order to check the adequacy of the chosen methods or measuring techniques.

Conclusions

Each karst system is unique, and the geometry of its different parts can be rather complex. Due to very strong lateral and vertical changes of the physical and lithological properties in karst regions, the main goal of exploration is to acquire a precise 3D geological model of the underground. Geophysical methods can play an important role in building such a model for two main reasons. Firstly, on the basis of geophysical results, the optimum locations and quantities of exploration boreholes can be defined which can have great implications on the total exploration cost. Secondly, geophysical methods can provide for continuous coverage over an exploration area, connecting data from boreholes to build a complete 3D model. Wide spatial covering and rapid sampling (dense spatial coverage), low cost and fast data interpretation are the main advantages of geophysical methods compared to traditional geological, hydrogeological and geomorphological studies. Finally, 3D-data-acquisition development for many geophysical methods holds great promise for karst-system exploration.

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