TITLE: KNOWLEDGE OF THE INTERNAL STRUCTURES OF KARST AREAS USING GEOPHYSICAL TECHNIQUES: A CASE STUDY OF MAMBAÍ (GOIÁS, BRAZIL)

JOURNAL NAME: REVISTA BRASILEIRA DE GEOMORFOLOGIA

TITLE: DETERMINING GEOPHYSICAL PROPERTIES OF A SHALLOW CAVE: A STUDY OF BRAZILIAN CAVE

JOURNAL: CATENA

USO DE GEOFÍSICA APLICADA OBJETIVANDO SUBSIDIAR O MAPEAMENTO GEOLÓGICO, MAPEAMENTOS E CONDUTOS E VULNERABILIDADE DO SISTEMA CÁRSTICO

Prepara as mapas e faz mapeamento de vulnerabilidade de águas subterrâneas.

Yawar Hussain

July, 2019

SUMMARY

This report aiming at describing the activities carried out in the month of July. The focus of activities remained on the finishing of articles. The activities are presented in form of two articles in preparation. 3D plotting of the results will be carried out soon.

During my one year post doctoral studies I have tried for the section of an appropriate model that can be applied to the study area. Attempts have also been made for linking geophysical techniques as the sources of some of the input data layers for the vulnerability assessment models.

In first stage of my study an extensive review of the available vulnerability assessment models for the Karst aquifer was done. In the next stage, an extensive study was carried out for the conceptualization of the groundwater flow stems in the environmental protected area of Vermelhio River. Then, based of this conceptualization two vulnerability assessment models after modifications were found appropriate for the area.

EPIK-Model:

COP-Model:

Geophysical data input: following input data layers can be obtained (i) soil types and soil thickness that can be obtained using geophysical techniques Ground Penetration Radar (GPR), (ii) Lithology and the presences or absence of fractures can be mapped using Electricity Resistivity Tomography (ERT), (iii) Another outcome of the seismic geophysical technique such as Multi-Channel Analysis of Surface Waves and seismic refraction can provide sub-surface stratification with reference of degree of compaction which is a import factor in the vulnerability of groundwater. (iv) Geophysical technique, Very Low Frequency Electromagnetic (VLF-EM) can help in identification of fractures and caves with water. The presence of water in the caves and fractures have paramount impacts on the vulnerability potential of the site.

For the geophysical site characterization of the area, in first stage a question is answered which geophysical technique is appropriate in the sub-surface site characterization in reference to its vulnerability. To this end a small portion over Tarimba cave was chosen. This site was close to a road, the area was flat and have a know position of cave. At this site all proposed geophysical techniques (e.g. ERT, GPR, MASW, Refraction and VLF-EM) were applied on a circular array. This array was chosen because it was a suitable option for the 3D mapping of the cave in subsurface. The preliminary results of these technique are written in the form of research articles attached below.

Future directions: Two under graduate students are working on the geophysical site characterization on larger area at Tarimba cave. After their works the conclusion will be drawn.

One Master student is working on the soil types and thickness mapping of the entire area using geophysical technique GPR as described above.

A doctoral student is working on the vulnerability assessment of the area using proposed models under my co-supervision. He will use the possible results as input layers in modeling the aquifer.

Two articles will be published soon in the following journals:

(i) Knowledge of the internal structures of Karst areas using geophysical techniques: a case study of Mambaí (Goiás, Brazil), **Revista Brasileira de Geomorfologia**.

(ii) Determining geophysical properties of a shallow cave: a study of Brazilian cave, **CATENA**.

Knowledge of the internal structures of Karst areas using geophysical techniques: a case study of Mambaí (Goiás, Brazil)

Abstract

Geophysical site characterization related to information of the internal structures of the Karst system can provide a cheaper and non-invasive alternative. In the present study, geophysical techniques such as Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT) are applied in an environmentally protected area of Rio Vermelho, Mambaí, Goiás. In data acquisition phase, the GPR and DC resistivity profiles were taken at two different locations as a road site and a cave site. Data were processed using commonly applied processing work flow in RelexW and RES2DINV softwares. Results of GPR showed a well defined lithology of the site (Limestone, Sandstone and the Pelitic rocks). On the inverted resistivity cross-sections a horizontal layering at the profile taken near the road site, while the presence of fractures and sinkholes are well identified on the two profiles taken parallel and perpendicular to the Tarimba cave. Our results so far encourage the use of GPR and ERT in the site characterization of the Karst areas.

1 Introduction

Karst occurs due to the underground natural cavities that are resulted from the erosive effect of groundwater (dissolution) on the surface of the carbonate rocks (Abidi et al. 2018). These features are with or without opening on the surface (Mohamed et al. 2019). Therefore, accurate subsurface karst detection can play an important role in the groundwater contamination and associated hazards which may cause the losses of properties such as structural and infrastructural problems (road and highway subsidence, building-foundation collapse, dam leakage), lives of people (Gambetta et al. 2011; Youssef et al. 2016).Hence, these underground cavities need to be well detected before the construction of any civil structures and groundwater managerial plans for such areas. Another importance of the cave lie in the fact that it can provide safe and consistent habitat for the species (ref).

The karst areas are the subject of many studies such as archaeological, environmental hydrogeological, geological, geotechnical and geomorphological. These studies provide incomplete information about the degree of karstification without any indication about the internal structures of the area (epikarst, infiltration zones, karst conduits, cavities, presence and type of overlying sediments and thickness). The analysis of internal structures (knowledge and geometry) of Karst is a challenging task because of the uncertainties created by the karts heterogeneities. The knowledge of karst internal structures is highly import in the vulnerability assessment of the karst aquifers (infiltration-property distribution) because of its influence on the infiltration conditions. The presence and thickness of overlying sediments ca slower and diffuse infiltration, while the presence of holes or dolines and absence of soil covert can fasten it (Andreo et al. 2009; Daly et al. 2002; Kavouri et al. 2011). In these scenario the detections of voids using non-invasive techniques are highly important.

For the identification and mapping of sinkhole in the sub-surface, the non-invasive and high resolution geophysical techniques appeared as an appropriate choice (Smith, 1986; Zhou et al., 2002; Ezersky, 2008; Krawczyk et al., 2012; Martinez-Moreno et al., 2013; Argentieri et al., 2015; Pazzi et al. 2018).

In the case of natural cavities which are usually filled with either water, air or collapsed material create a contrast in physical properties comparative to the surrounding rocks. These physical contrasts can be detected with geophysical techniques (Bishop et al., 1997). The onside of cavities cavities lead to the disturbance in the surrounding rocks which are extended away from the cavity (Pazzi et al. 2108). ERT and GPR are considered to be an appropriate techniques, as both of these are able to provide high-resolution images of the subsurface settings and can distinguish different types of sedimentary fillings in the cavities (Pazzi et al. 2108).

Karst terrains are widespread in Brazil specially, in the central and eastern portions of the country, where carbonate karst which are characterized by horizontally bedded and dolomite limestone having little or no relief developed under the influence of seasonal climatic variations (Auler and Farrant, 1996). The caves are divided into two groups as carbonate karst and non-carbonate karst of which carbonate karst is relatively more studied, however, the study of karst in Brazil is still in infancy stage and require detailed analysis (Auler and Farrant, 1996).

The present study applies geophysical techniques for the site characterization of the Tarimba cave. The geophysical measurements were performed at various sites on the karst system aiming at i) obtaining a suitable geological and hydrogeological model of the area, ii) detecting possible cavities/sinkholes and iii) suggesting possible paths for water infiltration. The study after following recommend suggestions will prove effective in the site characterization of the Brazilian Karst.

2 Material and Methods

2.1 Study area

The projected area is located at the junction of the municipality of Mambaí, having geographic coordinates: UTM 23L 373343 Long 8406394 Lat (Figure 1). The Tarimba cave has more than 2 entries and more than 11 km in length mapped into several conduits and halls is not yet fully mapped. The Gruna of Tarimba is undoubtedly one of the most important caves in the region and is one of the largest in the country in horizontal projection. The climate of the region is tropical with dry and rainy season.

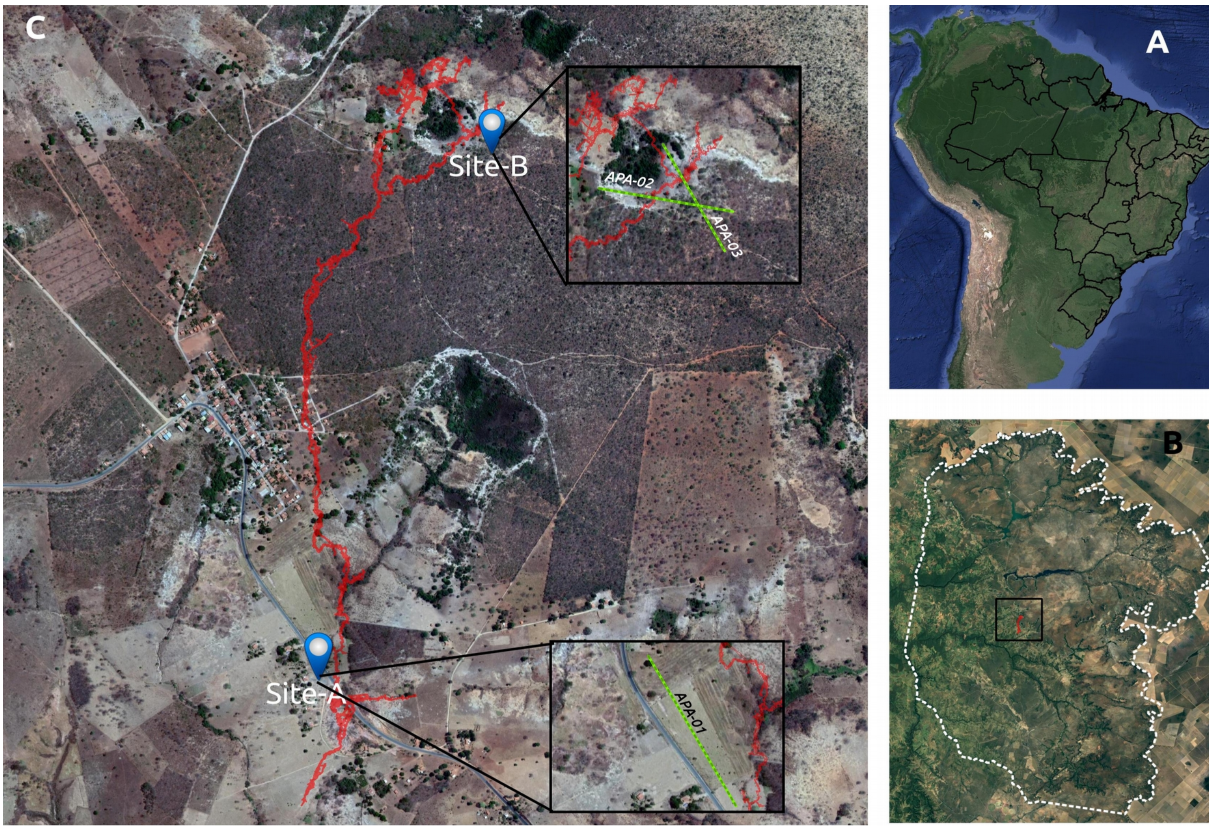

Figure 1 (A) Location of Brazil on the map of South America, (B) location of Tarimba Cave on environmentally protected area of the River Vermelho and (C) Locations of studied sites on Tarimba cave. Inserts show the zoom images of the survey sites along with positions of geophysical profiles.

In the APA area there are numerous rivers such as: Currente, Vermelho e Buritis. The main streams are: Bezerra, Piracanjuba, Rizada, Chumbada and Ventura and depressions commonly called grotta, which have water only in the rainy season, forming the drainage network. The Rivers and streams characteristics of planar areas, with occurrences of gradients and valleys. Some water courses penetrate into the soil becoming subterranean and later surfacing, promoting the formation of caves and caves of great interest (LOBO et al. 2015).

According to the aforementioned studies, the northeast region of Goiano presents lands with stratigraphic records of the Archaean, Proteozoic, Mesozoic and Cenozoic, most of which Proterozoic, which includes the following units: Ticunzal formation, sequence volcanic-sedimentary rocks of Palmeirópolis and São Domingos, Arai Group, Serra Branca, Tonalito São Domingos, Paranoá Group and Bambuí Group. The Bambuí Group is the most extensive carbonate unit and hosts the largest number of known caves in the Brazil (Auler, 2002). The Urucuia formation representing continental fluvial deposition, restricted to the eastern portion of the area, attributed to the Cretaceous, land of Mesozoic age. The Cenozoic is represented by the current fluvial deposits, alluvial and colluvial sandy deposits and by detritus-lateritic cover.

The northeastern region of the State of Goiás is in contact with several geomorphological domains. Their features are evidenced by the morphostructure climate reworked, contrasting dissected and recessed forms, interposed conserved forms, which represent remnants of the oldest topography. It is drained by the Paraná and Maranhão Rivers, which forms the Tocantins River. For the Northeast region of the State of Goiás, the following Soil classes: latosols, podzolic, cambisols, plinthsol, gleysol, sands hydromorphic quartzs, organic soils, quartz sands, alluvial soils, soils litholic, petroplinthic soils.

2.2 Electrical Resistivity Tomography (ERT)

The ERT method is based on injecting a known amount of current to the ground by two metal electrodes called current electrodes. The amount of current encounter resistance from the subsurface soil conditions (degree of fractures, material types and degree of saturation) and a potential is developed which is measured by two other metal electrodes know as potential electrodes. The method is affected by the geometry of deployment of these four electrodes on the surface and hence the technique can be used in three basic ways: 1) vertical electrical sounding (VES) 2) profiling and 3) electrical tomography where a large number of electrodes and combinations of electrode pairs are used. VES is quick and results are easy to process and interpret. However, it is limited to vertical resistivity variation (1-D assumption) (Strelec et al., 2017) and long acquisition profiles are required in order to reach greater depths. Another drawback of method is its data explanation by infinite solution (non uniqueness problem). While in the case where there are lateral and vertical variations, the application of VES become questionable. However, the resistivity tomographic techniques that provide 2D and 3D image of area are adopted as standard geophysical imaging techniques.

2.3 Ground Penetrating Radar (GPR)

Different geophysical methods have different resolution; with resistivity and seismic refraction having coarse resolution and GPR having the finest resolution depending on the antenna used. Ground Penetration Radar (GPR) is a geophysical technique in which subsurface image is obtained by passing electromagnetic waves of various frequencies through the earth. These energies are radiated from the antenna, which either absorbed or reflected back form the underlying material properties like fractures, moistures and clay contents. The energy reflected by the surface discontinuities is received by the receiver, which helps in subsurface image construction. The amplitude of radar pulse is an important attribute because it can carry information about the ground. After time to depth conversion, these amplitudes help in mapping the subsurface discontinuities (both physical and chemical). Higher the contrast at the interface of these discontinuities higher the amplitudes and vice versa.

2.4 Data Acquisition and Processing

The data acquisition phase consists of three days field campaign. A total of 72 electrodes were used for the injecting current in the subsurface as well as to measure the potential difference developed in response to these currents. The length of each profile was taken as 360 meters with electrode separation of 5m of dipole-dipole configuration (Figure). Three ERT profiles with same configuration was used at the two different sites as road site (APA-01) and the Tarimba cave site (APA-02; APA-03). The profiles at Tarimba passes parallel and perpendicular to the cave (Figure 1).

A preliminary data processing of the obtained resistivity data were carried out that includes, saving the data in computer from Syscal resistivity meter, where the further processing will be carried out. Then in the next stage, data of each line were opened in Prosycal II software again in order to see the anomalies and error in the data. Those resistivity values which were quite high had been manually removed from the data. The resistivity data can only be interpreted after inversion in the RES2DINV software.

The GPR survey was performed using a georadar device GPR GSSI SIR 3000, with 400MHz Antenna, Control Unity and Rugged Survey Car, in order to obtain a good resolution. For GPR data processing and visualization, Reflex-W software was used where the following basic steps were employed: (i) removal of the direct wave by subtracting the mean trace from each recorded trace; (ii) adjusting the start time to the actual direct wave onset on each trace; (iii) bandpass filtering to improve signal/noise ratio; (iv) gain adjustment to recover signal attenuation with depth.

3 Results and Discussions

3.1 Electrical Resistivity Tomography (ERT)

The ERT results of Site-A don't present any fractures and the presence groundwater in the subsurface. It is interesting to know that the subsurface material show a pattern which shows that the area is not disturbed structurally. The upper layer shows clay with high degree of moisture. This moisture content decreases with depth. Below the clay there is an interface of pelitic rocks. It is clear from the results (Figure 2) that Tarimba cave don't passing through that area.

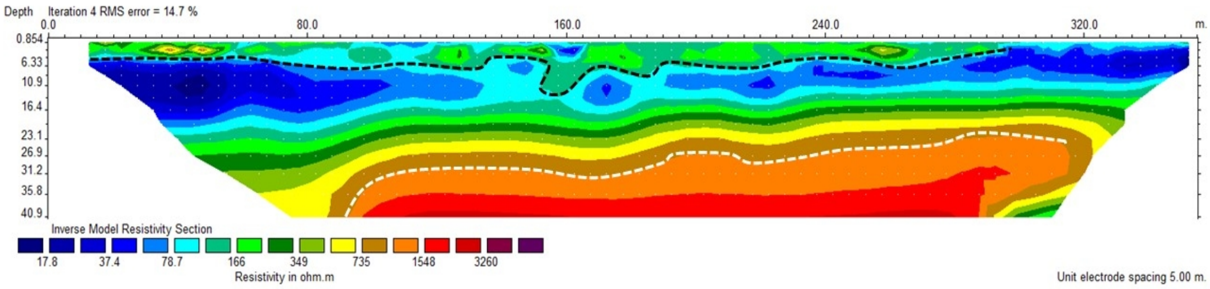

Figure 2 The modeled earth resistivity pseudo-sections for APA-01 ERT profile at the Site-A (road). Color bar presents resistivity values in hom.m.

The results of two resistivity profiles taken in the area near the entrance of the Tarimba cave (Figure 1). Here in these areas ERT was successfully able to mark the presence of fractures, sinkholes and different soil types. At the middle of profile APA-02, a high resistivity material encountered which can be linked with sinkhole filled with dry and coarse grained material (Figure 2). It can be seen that water entered through the fracture and travel downward and is shown as a low resistivity zone on the center of the profile (Figure 3). At the right side of the profile sandstone with various degree of moisture is found. The out crop of the limestone is also found on inverted resistivity cross-section which are supported by the on-site visits.

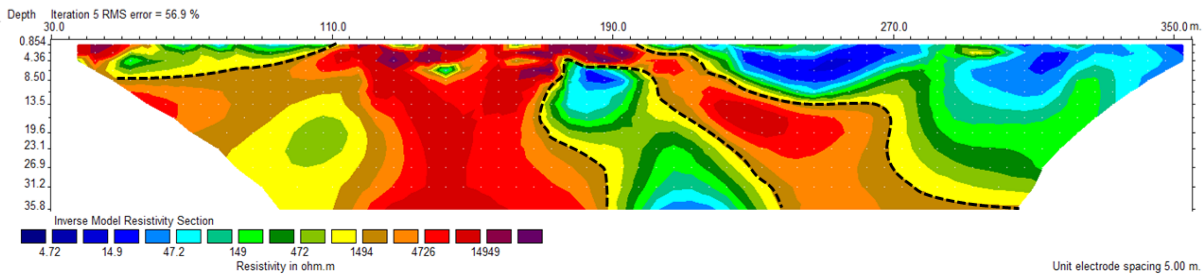

Figure 3 The modeled resistivity pseudo-sections for APA-02 ERT (Tarimba cave) profile. Color bar presents resistivity values in hom.m.

In the upper layers, different resistivity layering are obtained which can be linked with the different soil types and degree of soil moisture. The carbonate rock are very prominent on the profile APA-03. A low resistivity zone is found at 31 m depth which can be investigated further for groundwater prospecting. Above this low resistivity zone a depression of low resistivity material found which may possible be linked with a filled sinkhole. The fracture is filled with low resistivity material.

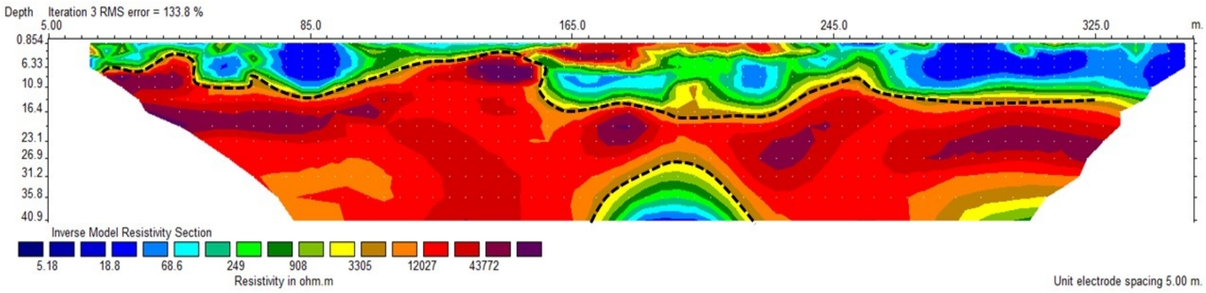

Figure 4 The modeled resistivity pseudo-sections for APA-03 ERT (Tarimba cave) profile. Color bar presents resistivity values in hom.m

3.2 Ground Penetrating Radar (GPR)

A profile was taken out side the cave at a location where various lithologies were present. Figure 5 shows the vertical cross-section of the sub-surface of the area. At the beginning of the profile there is sandstone through which the electromagnetic wave can pass easy. As a result high amplitude reflection are observed on the 2-D cross section obtained. At the end of profile there are patches of limestone the presence of which cause some radar wiggles of high amplitude to appear on the cross-section. However, it is interesting to note that in the middle portion some wavy wiggles are observed, these are noisy events created by the passing of four wheeler vehicle used for the GPR data acquisition. This phenomenon occurs because GPR antenna don't touch the soil, which is cause of some noisy wiggles on the GPR cross section.

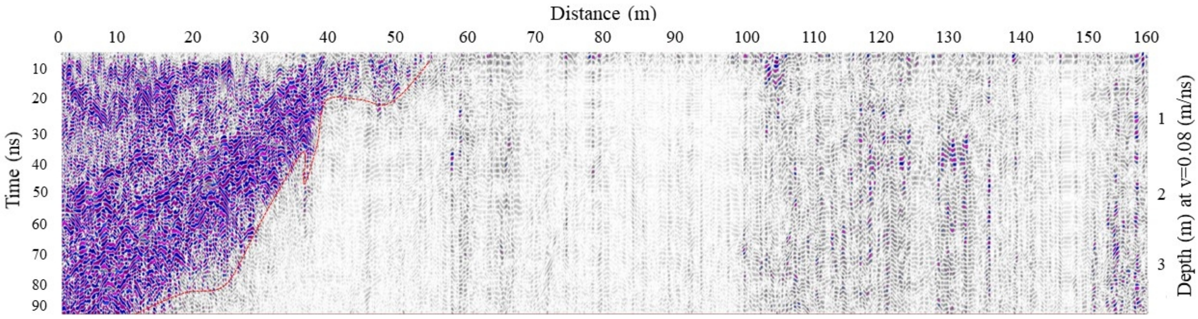

Figure 5. These lithologies are marked on GPR cross-section as A) Sandstone, B) pelitic rocks and C) Intrusion of the small patches of limestone.

4 Conclusions

The study was carried for the soil and rock characterization as well for the estimation of sediment thickness inside the cave. Following conclusions are drawn from the analysis (i) On GPR profiles it was very easy to differentiate different rock units. In this way the GPR has proved an attraction choice for the site characterization in karst system. With the use of GPR the sediment thickness inside the cave is done. For the better speleology of the cave a new GPR survey with high frequency (900mHz) antenna. The GPR/ERT geophysical investigation determined the spatial position and depth of sedimentary filling, thus creating a sound basis for further studies. (ii) On resistivity section obtained at the road site don't show the presence of cave or the groundwater. However, the inverted resistivity sections at the cave site shows the presence o0f cave and fractures which are recommend to test further for the groundwater prospecting.

References

Abidi, A., Demehati, A., Banouni, H., & El Qandil, M. (2018). The Importance of Underground Cavities Detection in the Choice of Constructible Areas: Case of the Agglomeration of Fez (Morocco). **Geotechnical and Geological Engineering**, 36(03): 1919-1932.

Andreo B, Ravbar N, Vias JM (2009) Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: application to pilot sites. **Hydrogeology Journal**, 17:749–758.

Argentieri, A., Carluccio, R., Cecchini, F., Chiappini, M., Ciotoli, G., De Ritis, R., Di Filippo, M., Di Nezza, M., Marchetti, M., Margottini, S., Materni, V., Meloni, F., Nardi, A., Rotella, G., Sapia, V., Venuti, A., (2015). Early stage sinkhole formation in the Acque Albule basin of central Italy from geophysical and geochemical observations. **Engineering Geology**, 191, 36-47.

AULER, A. S. (2002). Karst areas in Brazil and the potential for major caves-an overview. *Bol. Soc. Venezolana Espel*, *36*, 29-35.

Auler, A., Farrant, A. R. (1996). A BRIEF INTRODUCTION TO KARST AND CAVES IN BRAZIL. *Proceedings of the University of Bristol Spelaeological Society*, *20*, 187-200.

Bishop, I., Styles, P., Emsley, S.J., Ferguson, N.S., 1997. The Detection of Cavities Using the Microgravity Techniques: Case Histories from Mining and Karstic Environments. **Engineering Geology Special Publications**, pp. 153-166.

Čeru, T., Gosar, A., & Šegina, E. (2017, June). Application of ground penetrating radar for investigating sediment-filled surface karst features (Krk Island, Croatia). In 2017 9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR) (pp. 1-6). IEEE.

Chalikakis, K., Plagnes, V., Guerin, R., Valois, R., Bosch, F. P. (2011). Contribution of geophysical methods to karst-system exploration: an overview. **Hydrogeology Journal**, 19(6), 1169.

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu IC, Zwahlen F (2002) Main concepts of the European approach to karst-groundwater vulnerability assessment and mapping. **Hydrogeology Journal,** 10:340–345.

Dourado, J. C., Malagutti Filho, W., Braga, A. C., Nava, N. (2001). Detecção de cavidades em arenitos utilizando gravimetria, eletrorresistividade e GPR. **Revista Brasileira de Geofísica**, 19-32.

Ezersky, M., 2008. Geoelectric structure of the Ein Gedi sinkhole occurrence site at the Dead Sea shore in Israel. **Journal of Applied Geophysics**, 64, 56–69.

Fabregat, I., Gutiérrez, F., Roqué, C., Comas, X., Zarroca, M., Carbonel, D., ... Linares, R. (2017). Reconstructing the internal structure and long-term evolution of hazardous sinkholes combining trenching, electrical resistivity imaging (ERI) and ground penetrating radar (GPR). **Geomorphology**, 285, 287-304.

Kavouri, K., Plagnes, V., Tremoulet, J., Dörfliger, N., Rejiba, F., & Marchet, P. (2011). PaPRIKa: a method for estimating karst resource and source vulnerability—application to the Ouysse karst system (southwest France). **Hydrogeology Journal**, 19(2), 339-353.

Krawczyk, C.M., Polom, U., Trabs, S., Dahm, T., 2012. Sinkholes in the city of Hamburg -new urban shear-wave reflection seismic system enables high-resolution imaging of suberosion structures. **Journal of Applied Geophysics**, 78, 133–143.

LOBO, H. A. S., BICHUETTE, M. E., HARDT, R., de Souza MARTINELLI, R., BRUNO FILHO, F. G., GALLÃO, J. E., ... & CALVO, E. M. CARACTERIZAÇÃO AMBIENTAL PRELIMINAR E PROPOSTA DE CONSERVAÇÃO DO SISTEMA CÁRSTICO DA GRUNA DA TARIMBA–MAMBAÍ, GO.

M. Gambetta, E. Armadillo, C. Carmisciano, P. Stefanelli, L. Cocchi, and F. C. Tontini (2011) Determining geophysical properties of a near surface cave through integrated microgravity vertical gradient and electrical resistivity tomography measurements. **Journal of Cave and Karst Studies**,73(1):11–15.

Martinez-Lopez, J., Rey, J., Duenas, J., Hidalgo, C., Benavente, J. (2013). Electrical tomography applied to the detection of subsurface cavities. **Journal of Cave & Karst Studies**, 75(1).

Martinez-Moreno, F.J., Pedrera, A., Ruano, P., Galindo-Zaldivar, J., Martos-Rosillo, S., Gonzalez-Castillo, L., Sanchez-Ubeda, J.P., Marin-Lechado, C., 2013. Combined microgravity, electrical resistivity tomography and induced polarization to detect deeply buried caves: algaidilla cave (Southern Spain). **Engineering Geology**, 162, 67–78.

Mohamed, A. M. E., El Hussain, I., Deif, A., Araffa, S. A. S., Mansour, K., & Al Rawas, G. 2019 Integrated GPR, ERT and MASW for detecting near surface caverns at Duqm area, Sultanate of Oman. **Near Surface Geophysics**, 17(4):379-401.

Pazzi, V., Di Filippo, M., Di Nezza, M., Carlà, T., Bardi, F., Marini, F., ... Fanti, R. (2018). Integrated geophysical survey in a sinkhole-prone area: Microgravity, electrical resistivity tomographies, and seismic noise measurements to delimit its extension. **Engineering Geology**, 243, 282-293.

PUTIŠKA, R., KUŠNIRÁK, D., Dostál, I., LAČNÝ, A., MOJZESŠ, A., Hok, J., ... & BOŠANSKÝ, M. (2014). Integrated geophysical and geological investigations of Karst structures in Komberek, Slovakia. **Journal of Cave & Karst Studies**, 76(3).

Putiška, R., Sabol, M., Kušnirák, D., Dostál, I. (2017). Geophysical Research at the Prepoštská Cave and Čertova Pec Cave Neanderthal Sites (Western Slovakia). **Archaeological Prospection**, 24(2): 119-131.

Smith, D.L., 1986. Application of the pole-dipole resistivity technique to the detection of solution cavities beneath highways. **Geophysics**, 51, 833–837

Strelec, S., Mesec, J., Grabar, K., Jug, J. (2017). Implementation of in-situ and geophysical investigation methods (ERT & MASW) with the purpose to determine 2D profile of landslide. **Acta Montanistica Slovaca**, 22(4):345.

Youssef, A. M., Al-Harbi, H. M., Gutiérrez, F., Zabramwi, Y. A., Bulkhi, A. B., Zahrani, S. A., ... & El-Haddad, B. A. (2016). Natural and human-induced sinkhole hazards in Saudi Arabia: distribution, investigation, causes and impacts. **Hydrogeology Journal**, 24(3): 625-644.

Zhou, W., Beck, B.F., Adams, A.L., 2002. Effective electrode array in mapping karst hazards in electrical resistivity tomography. **Environmental Geology**, 42, 922–928.

Determining Geophysical Properties of a Shallow Cave: a Study of Brazilian Cave

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Abstract

Caves have greater importance in the fauna and flora of the region along with these, the study of Karst system is important because of the associated hazards such as sinkhole collapse and groundwater vulnerability which can cast dangerous effects on population as well as the civil engineering structures such as road, pavements and houses. The present study aiming at providing an introduction to the Brazilian caves based on the preliminary information obtained from the surveys carried out in Tarimba cave, Goais, Brazil. The applied geophysical approaches include Seismic Refraction Tomography (SRT), Electrical Resistivity Tomography (ERT) and Very Low Frequency Electromagnetic (VLF-EM). The 2-D sections of each measured physical properties (impedance contrast, electrical resistivity and induced current because of local body) were made in different softwares. For ERT data least square inversion was used while Karous-Hjelt filter was used for VLF-EM data. In SRT time-term inversion was used. Results of ERT and VLF-EM were found closer to the reality; however, seismic refraction method did reach the depth of cave because of shorter profile lengths. These integrated approaches will prove an effective tool for the site characterization of Karst system in Brazil in reference to the vulnerability assessment of groundwater.

Keywords: Karous-Hjelt filter; groundwater vulnerability; shallow cave; Tarimba cave

1 Introduction

Karst occurs due to the underground natural cavities that are resulted from the erosive effect of groundwater (dissolution) on the surface of the carbonate rocks (Abidi et al. 2018). These features are with or without opening on the surface (Mohamed et al. 2019). Therefore, accurate detection of Epikkarst can play an important role in the groundwater contamination and associated hazards which may cause the losses of properties such as structural and infrastructural problems (road and highway subsidence, building-foundation collapse, dam leakage), lives of people (Gambetta et al. 2011; Sundararajan et al. 2015; Youssef et al. 2016). Hence, these underground cavities need to be well detected before the construction of any civil structures and groundwater managerial plans for such areas.

To this end, geophysical methods can play a significant role in the detection as well as delineation of such subsurface cavities (Sundararajan et al. 2015). Over the past years, the near surface geophysical techniques have proved effective in the site characterization of Karst system (e.g. Martinez-Lopez et al. 2013; Dourado et al., 2001; Chalikakis, et al. 2011; Čeru et al. 2017; PUTIŠKA et al. 2014; Fabregat et al. 2017; Putiška, et al. 2017; Pazzi et al. 2018). Each geophysical technique measures a specific physical property of the subsurface material over karst area, these measured values are inverted through a process where observed and measured data are compared and a best-fit model is achieved (Desert et al. 2019). The geophysical responses recorded over caves work well because of relatively larger size and sharp contracts with the surrounding rocks (Konstantinos et al. 2011). Other important parameters that need to be kept in the mind are the thickness and type of sediments (clay content, density, soil moisture, etc.) at the site that can greatly affect the recorded geophysical signature of the investigated site. The presence of epikarst zone and its thickness is extremely important factor in the application of any geophysical technique (Konstantinos et al. 2011).

However, the Karst provides a complicated environmental because of the subsurface heterogeneities that make studies of groundwater, engineering and environmental problematic (Ford and Williams, 2007). Under these conditions, integrated geophysical techniques are recommended. Geophysical techniques such as Seismic Refraction Tomography (SRT), Electrical Resistivity Tomography (ERT) and Very Low Frequency Electromagnetic (VLF-EM) have a potential for the site characterization based on which areas can be recommended for the latter detailed geotechnical investigations (Oladotun et al. 2019).

The worldwide adaptability of geophysical techniques for the site characterization are Abbas et al. (2012); Krawczyk et al. (2012); Basheer et al. (2012); Stepisnik, (2008); Ford and Williams, (2007); Abidi et al. (2018). In the case of Brazil, the caves have not been studied extensively in the past. The geophysical studies of cave are even lesser. There are few studies applied for the analysis of caves as dos Santos et al. (2012); de Queiroz et al. (2018); Pereira et al. (2019); Brandi et al. (2019); Garcia and Grohmann, (2019). However, the caves in the environmentally protected area of the River Vermelho, there is no study applying geophysical investigation for the site characterization of Karst system there, which has increased the merits of the present study.

The main aim of the present study is to characterize Karst system in Mambaí, Goiás, Brazil using integrated geophysical techniques. The approach is adopted for a small portion of Tarimba cave using Electrical Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT) and Very Low Frequency Electromagnetic (VLF-EM). In the end, the suitability of these applied techniques are discussed and recommendations for the future studies are presented. Results of this study can be used in the establishment of new paradigms for the comprehensive study of caves, which will prove an effective step in natural hazards mitigation and groundwater managerial plans through observation, interpretation and understanding of the Karst system.

1.1 Study area

The projected area is located at the junction of the municipality of Mambai, having geographic coordinates: UTM 23L 373343 Longitude 8406394 Latitude (Figure 1). The Tarimba cave has more than two entries and its more than 11 km in length mapped into several conduits and halls. The has not been fully mapped yet. It is one of the most important caves in the region (fauna and flora) and is one of the largest in the country in horizontal projection. The climate of the region is tropical with dry and rainy season (ref).

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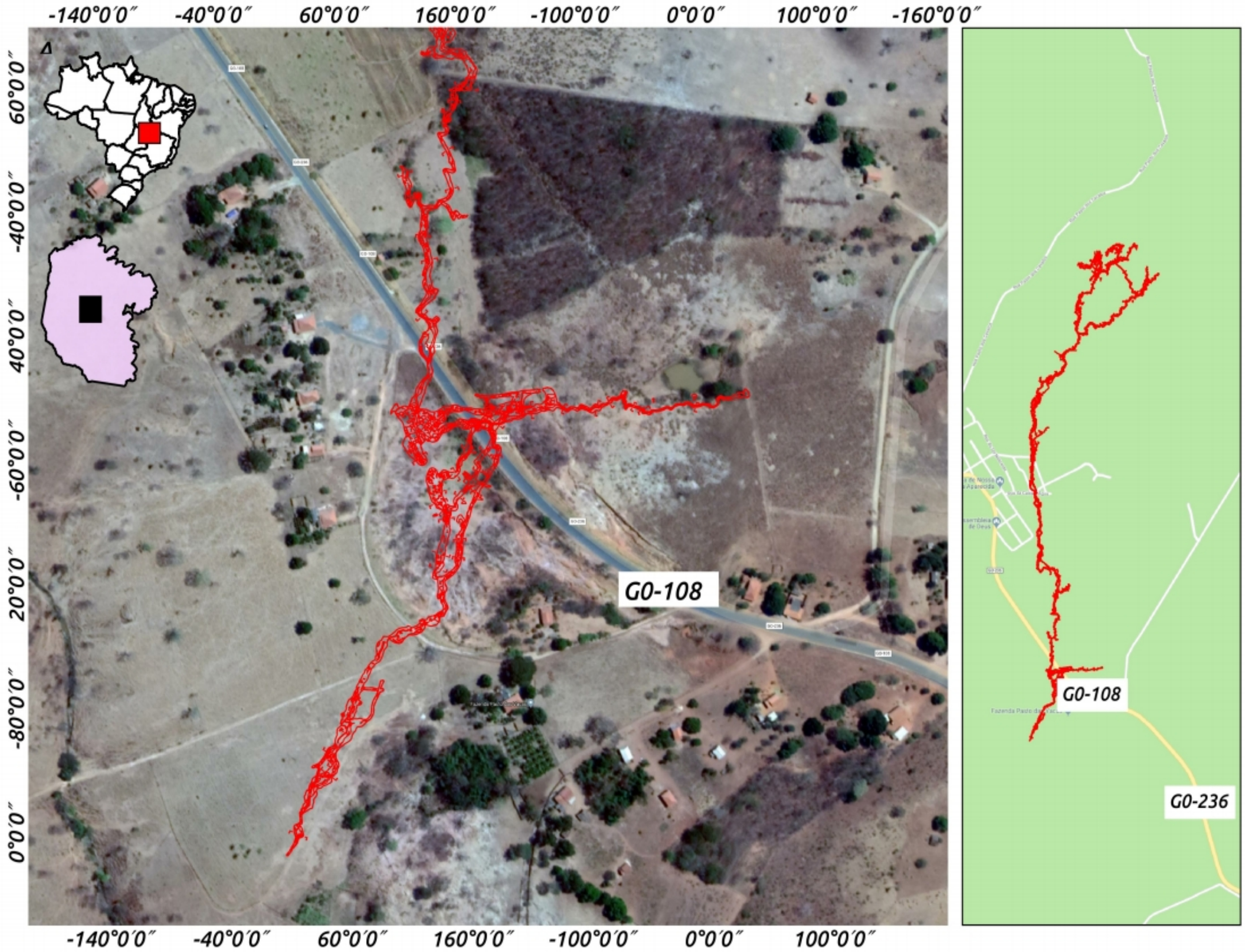

Figure 1 Location of study area on the map of Brazil, administrative boundary of environmental protected area of the River Vermelhio, location of the study area on Tarimba cave and the locations of geophysical profiles (ERT, SRT and VLF-EM).

1.2 Geology and Geomorphology

In the area, there are numerous rivers such as Currente, Vermelho and Buritis. The main streams are: Bezerra, Piracanjuba, Rizada, Chumbada and Ventura and depressions commonly called grotta, which have water only in the rainy season, forming the drainage network. The Rivers and streams characteristics of planar areas, with occurrences of gradients and valleys. Some watercourses penetrate into the soil becoming subterranean and later surfacing, promoting the formation of caves that are of greater interest (Lobo et al. 2015).

In accordance with the previous studies, the northeast region of Goiano presents lands with stratigraphic records of the Archaean, Proteozoic, Mesozoic and Cenozoic, most of which are Proterozoic, which include the following units: Ticunzal formation, sequence volcanic-sedimentary rocks of Palmeirópolis and São Domingos, Arai group, Serra Branca, Tonalito São Domingos, Paranoá group and Bambuí group (ref).

The Urucuia formation representing continental fluvial deposition, restricted to the eastern portion of the area, attributed to the Cretaceous land of Mesozoic age. The Cenozoic age is represented by the current fluvial deposits, alluvial and colluvial sandy deposits and by detritus-lateritic cover (ref).

The northeastern region of the State of Goiás is in contact with several geomorphological domains. Their features are evidenced from the morphostructural climatic worked; contrasting dissected and recessed forms, interposed conserved forms, which represent remnants of the oldest topography. It is drained by the Paraná and Maranhão Rivers, which forms the Tocantins River (ref).

For the Northeastern region of the State of Goiás, the following soil classes are found latosols, podzolic, cambisols, plinthsol, gleysol, sands hydromorphic quartzs, organic soils, quartz sands, alluvial soils, soils litholic and petroplinthic soils (ref).

2 Methodology

2.1 Electrical Resistivity Tomography (ERT)

The electrical resistivity tomography (ERT) is an import method which works on the principle that the electrical resistivity of the host rocks (surrounding material) are lesser than caverns (Noel and Xu 1992; Manzanilla et al. 1994; Leucci and De Giorgi 2005; Elawadi et al. 2006; Araffa, 2010; Martínez-López et al. 2013; Kasprzak and Sobczyk 2017; Mohamed et al. 2019). The ERT method is based on injecting a known amount of current to the ground by two metal electrodes called current electrodes. The amount of current encounter resistance from the subsurface soil conditions (degree of fractures, material types and degree of saturation) and a potential is developed which is measured by two other metal electrodes know as potential electrodes. The method is affected by the geometry of deployment of these four electrodes on the surface and hence the technique can be used in three basic ways: (i) vertical electrical sounding (VES) (ii) profiling and; (iii) electrical tomography where a large number of electrodes and combinations of electrode pairs are used. VES is quick and results are easy to process and interpret. However, it is limited to vertical resistivity variation (1-D assumption) (Strelec et al. 2017) and long acquisition profiles are required in order to reach greater depths. Another drawback of method is its data explanation by infinite solution (non uniqueness problem). While in the case of the occurrence of landslide in an area there are lateral and vertical variations, under these conditions the application of VES become questionable. However, the resistivity tomographic techniques that provide 2D and 3D image of area are adopted as standard geophysical imaging techniques.

Applications:

The planning phase consists of a one day (22/11/2018) field visit in order to see the ground conditions for the survey lines (ERT, SRT and VLF-EM) over Tarimba cave. The array configurations to be used in the field for the acquisition of resistivity data was carried out in ELECTRE II software. Where the number of electrodes and space between them is specified and the software generates an automatic configuration file, which provide the maximum depth of investigation. The other acquisition parameters such as time, voltage and number of data points were also defined using the same software. An electrode spacing of 5 meters with a profile length of 360 meters was optimized after testing different electrode spacing. A total of 72 electrodes will be used in resistivity survey. The acquisition parameters were transferred to the resistivity meter to be used in the field. A preliminary data processing of the obtained resistivity data were carried out in Prosyscal II software that includes, saving the data in computer from Syscal resistivity meter, where the further processing will be carried out. Then the anomalies and error in the data are seen in the software and the resistivity values which were quite high are removed manually from the data. After editing the data is saved in a new file format compatible with RESIS2DINV of Geotomo Software (Loke, 2004), where the inversion of resistivity data is performed. In this software, a best fit earth model is generated from the apparent resistivity values. For that cell based resistivity calculation is made through the application of smoothness-constrained least-squares inversion method (Sasaki,

1992) that search for an idealized model for the resistivity distribution in the subsurface and its best fit with the calculated measured resistivity values (Colangelo et al., 2008). In this method, the subsurface is divided into rectangular blocks each representing single measuring point (Lapenna et al., 2005). The root mean square error (RMS) provides the discrepancy between measured and calculated values.

2.2 Seismic Refraction Tomography (SRT)

Seismic waves traveling in subsurface materials can undergo reflection, refraction and diffraction at any material interface and are traveled at different speeds in the subsurface before reaching at receiver. These variations in travel time is used for the subsurface image (Akpan et al. 2018). In Seismic Refraction Tomography (SRF) technique, the differences of the seismic waves travel-times are utilized for the subsurface imaging. There are methods used for the inversion of seismic refarction data as (i) Time term least squares and (ii) Delay-time (reciprocal) (Nogueira et al. 2014).

The shallow seismic tomography is an excellent choice for estimating the depth of different geological interfaces for different purposes such as geotechnical (Shebl et al. 2019) and engineering geological investigations (Attwa and Shinawi, 2017) and for the site characterization of landslide areas (McClymont et al. 2016; for hydrogeological analysis (Prekopová et al. 2016); as well for archaeological exploration (Shahrukh et al. 2012; Brixová et al. 2018) and site characterization of Karst (Azwin et al. 2013; Brock-Hon et al. 2019).

For the data acquisition of shallow seismic refraction, 48 receivers with inter receiver (geophones of 14 Hz frequency) distance of 5 m were used. SRF technique was carried out with a 24-Channel, 12V-DC Battery, a roll of trigger cable, 2 seismic cable reels. Four seismic sections of 120 m length of each were acquired (Figure 1). The positions of the shots for each line were at –10, 0, 57.5 and 125 meters, from the first geophone. The data was acquired with Geode (Geometrics) seismograph and the data processing was applied in software package Zond2D (demo version). Processing steps???Inversion write from Azwin et al. 2013

2.3 Very Low Frequency Electromagnetic (VLF-EM)

Very Low Frequency Electromagnetic (VLF-EM) is a semipassive electromagnetic induction method which utilizes the signals (primary field) released from distant high power vertical transmitters (15–30 kHz), installed on coastal regions. The signals are propagated between surface of earth and ionosphere and can reach a long distance and can be used for geophysical measurements. This method is ideal for the detection of vertical and dipping conductive subsurface structures such as conductive elongated structures, geological contacts like altered zones, faults, conductive dykes and cave with water because the primary field is horizontal.

In the case of subsurface conductor (fractures with water), a secondary field is induced in the conducting body. The induced field which is superimposed on primary field is differ in phase. These primary and secondary fields are measured on the earth surface with VLF-EM receiver which can help in detecting the conductive bodies (Guerin et al. 1994). The depth of penetration is considered as more than 30 m (Fraser, 1969) and is a function of geometry and dimensions of the host medium and the anomalous bodies and the frequency used.

For the acquisition of VLF-EM data, same acquisition profiles were used as for ERT and SRT. In the first stage, the quality of signals were assessed based on the results. For data acquisition along the predefined profiles, a Juno 3D Trimble GPS and a T-VLF unit of IRIS- Instruments, 1993 receiver was used. In the survey, the tilt angle mode was used in the field.

Both filters ? provide a good preliminary outline of how the target can be resolved semiquantitavely. Ogilvy and Lee (1991) state that, the 2-D current density distribution can be used for the identification of subsurface targets. The powerful VLF data filtering (Fraser and Karous-Hjelt) can be applied in different softwares (e.g.,VLFMOD , EMIXVLF , RAMAG , KHFFILT , INV2DVLF, VLFPROS) (Al-Oufi et al. 2008). With the aid of these softwares the contoured maps of the current density are made which make interpretation easy.

The VLF-EM method is a popular EM tool for quick mapping of near-surface structures for groundwater exploration (Sundararajan et al. 2007; Babu et al. 2007). There is a worldwide network of VLF stations that generate signals to be used for a variety of applications, including groundwater exploration (Hayles and Sinha, 1986; Al-Tarazi et al. 2008); soil engineering, archeology, and mineral exploration for mapping narrow mineralized fault zones (Babu et al. 2007 and references there in), mapping of weathered layers in granitic terrain (Poddar and Rathor, 1983); lava tubes, faults and dikes (AL-OUFI et al. 2008) and zones of potential subsidence (Dindi, 2015). for cave ?

3 Results and Discussions

3.1 Electrical Resistivity Tomography (ERT)

Carbonate has high resistivity generally about 1000 ohm.m and of loamy sediments is lower than 250 ohm.m (Telford) et al. 1990; Zhou et al. 2000; Stepisnik, 2008). So, we define three ranges of resistivity: high for r>250Wm; intermediate for 250Wm>r>150Wm, and low for r<150Wm. We assume that the intermediate values as the presence of cave adopted from Dos Santos et al. (2012). In the case of cave that are partially or completely filled with brine water (resistivity is always lower than 150Wm) or clay make ERT a suitable geophysical technique because they are more conductive than limestone and air (resistivity always higher than 250Wm) (Dos Santos et al. 2012). The resistivities of the detected varies based on the presence of water. The dry part of the cave has higher resistivity than the parts having water (Figure).

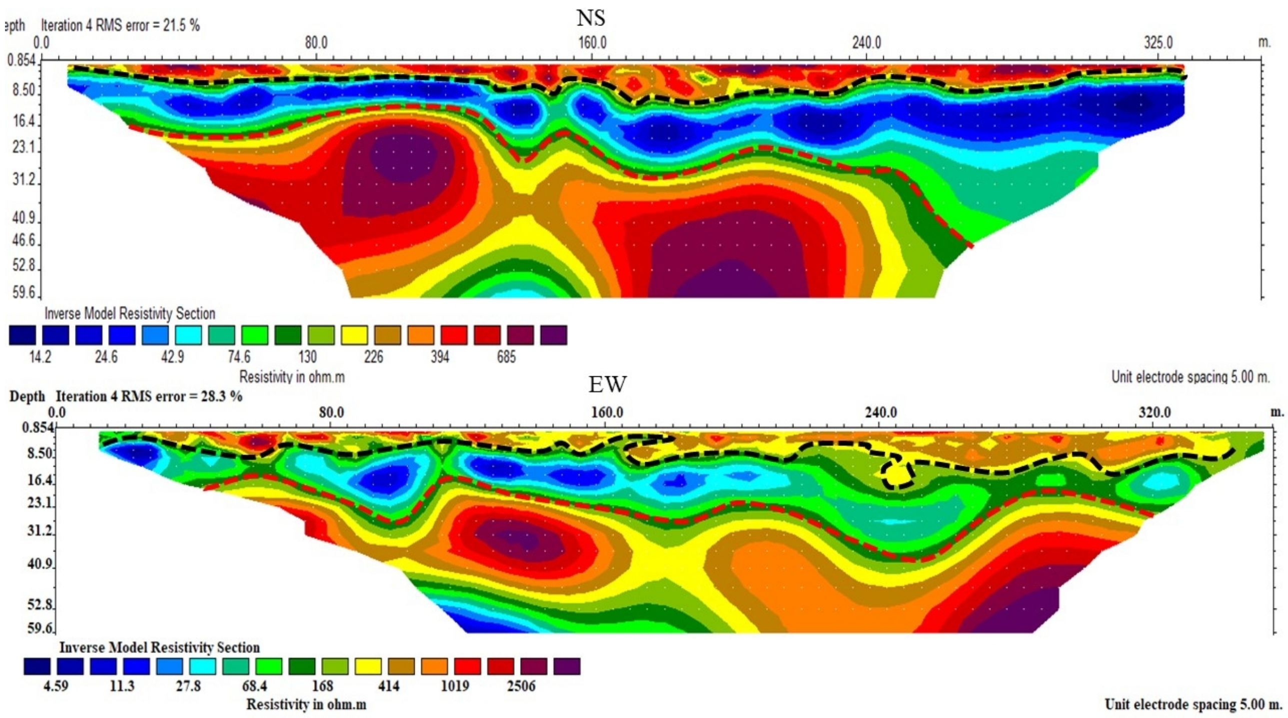

Figure 2 Electrical Resistivity **r**esults collected using a dipole-dipole along a circular array (NS and EW lines) with 5m spacing covering a distance of 350m and a depth of 59m. Black and red dotted lines represent the thickness of top soil and roof of cave, respectively.

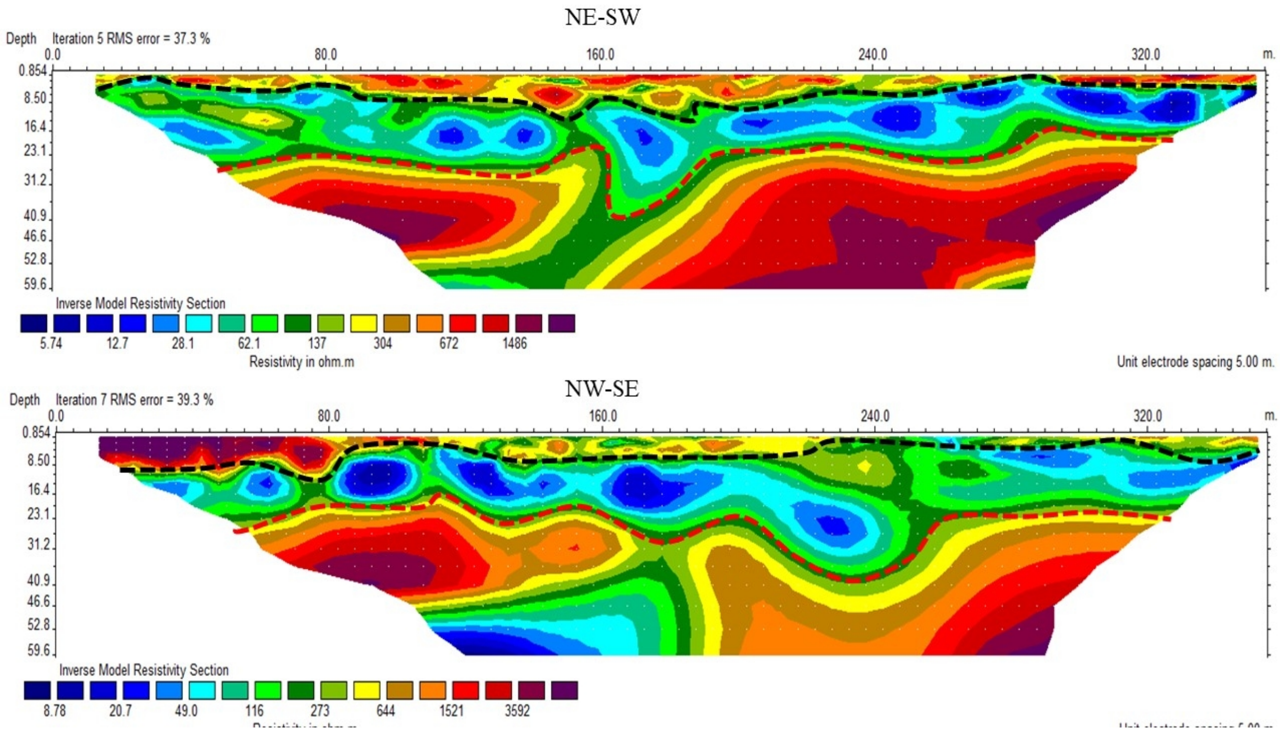

Figure 3 Electrical Resistivity **r**esults collected using a dipole-dipole circular array, NE-SW and NW-SE lines with 5m spacing covering a distance of 350m and a depth of 59m. Black and red dotted lines represent the thickness of top soil and roof of cave, respectively.

3.2 Seismic Refraction Tomography

Results from SRT reveal three main seismic velocity zones, which correspond to the three main lithological units as topsoil, claystone and compacted claystone over the cave. The upper zone comprises soil, characterized by low seismic wave velocities (3000-3500 m/s), and thickness ranges from 3 to 6 m. The intermediate layer has wave velocities of 1000-2400 m/s. The third layer shows a comparatively high velocity on all profiles, which may be associated with the presence of compacted claystone (Figure 4, 5). On all profiles a continuous increase in the velocity with depth is observed which shows a degree of compaction with depth. The results of SRT remained unsuccessful in identification of caves as detected on the ERT profiles, due to the depth limitations associated with the length acquisition profiles in the area.

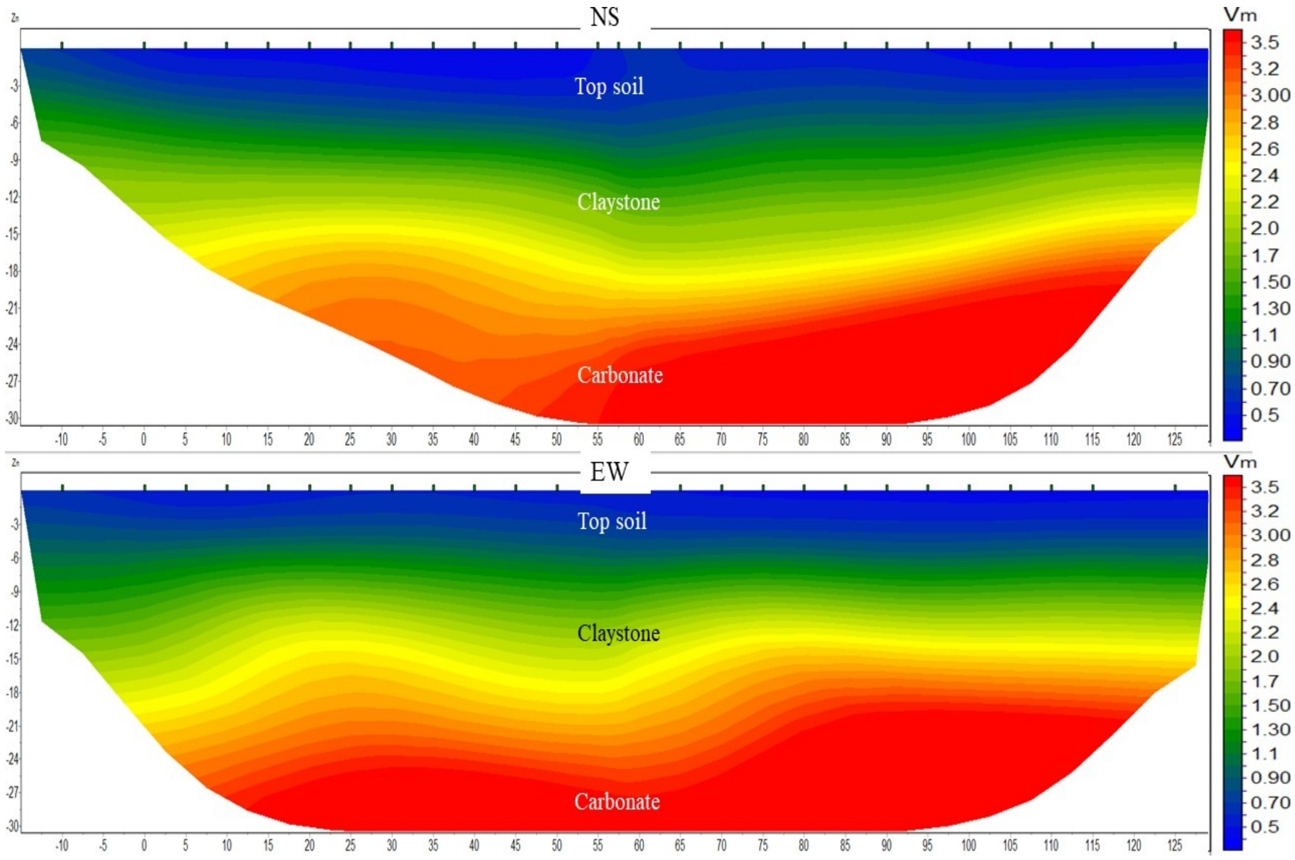

Figure 4 Seismic refraction image of the study area, indicating the number of layers (topsoil, claystone and compacted claystone), p-wave velocity of each layer and depth of investigation.

It is interesting to note that the velocity of third layer is relatively lower in the beginning of profile than at the profile end (Figure 4). This contrast show a lesser degree of compaction on right side. On the NE-SW profile reverse is true. However, on profile NW-SE this trend of decreasing compaction appeared again (Figure 5). May be associated with presence of groundwater?.

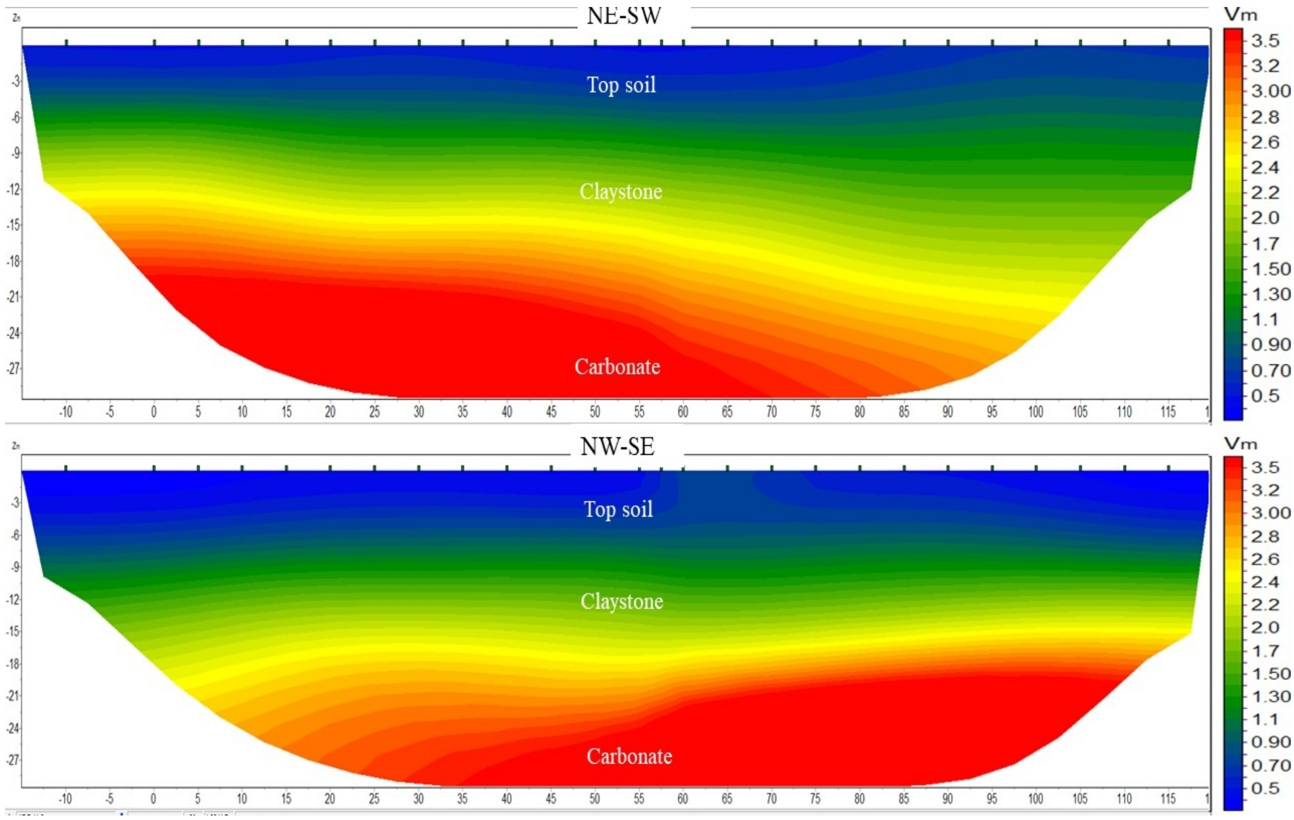

Figure 5 Seismic refraction image of the study area, indicating the number of layers (topsoil, claystone and compacted claystone), p-wave velocity of each layer and depth of investigation.

3.3 Very Low Frequency Electromagnetic (VLF-EM)

The VLF data were interpreted qualitatively to determine the location of subsurface caves . The profiles (NS and EW) performed in the study area showed number of anomalies that vary in both size and amplitude (Figure 6). The observed current density anomalies are divided into two main types as positive and negative, suggesting that the body is a conductor or resistive, respectively (Al-Oufi et al. 2008). The measured tilt angle (real component) for each frequency were presented in the form of contoured sections (Figure 6). VLF positive anomalies were detected at 100 and, possibly, at 320 m horizontal location. These anomalies were interpreted as conductive fracture zones with possible water. The conductive anomalies were also observed on the sections at 5m and 450 m on NS sections and a 100 and 300m on sections EW.

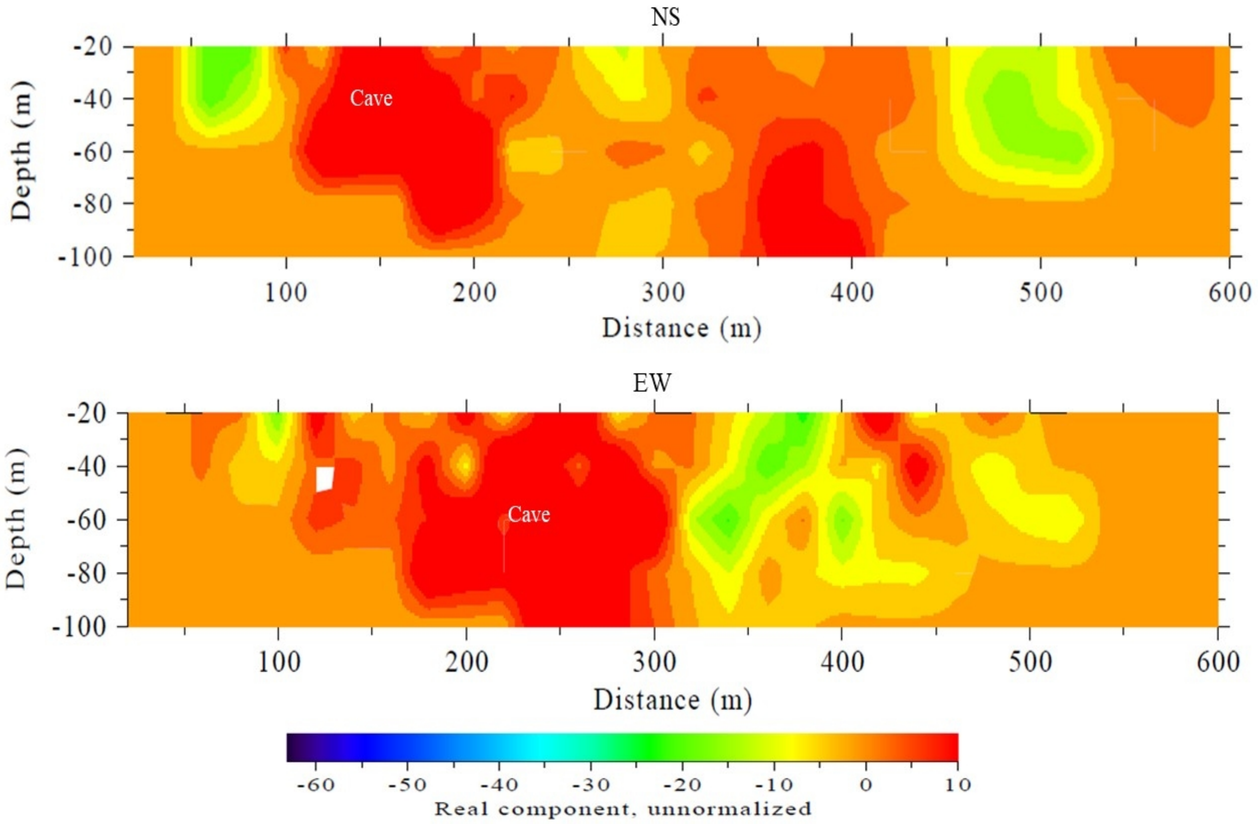

Figure 6 VLF results along the NS and EW lines. These sections shows high resistivity zones as a possible presence of cave.

Conclusion and Recommendation

The present study was carried out for the subsurface characterization over a cave at known position and depth using integrated geophysical techniques. Following conclusions are drawn from the analysis.

On the inverted resistivity sections three layered stratigraphy is obtained at comparatively greater depth. Caves are very clearly seen of the inversed sections in all directions. Thus it is concluded that the diameter of cave at the studied site was much higher than the already marked diameter. The low values of the apparent resistivity data indicate the parts of the caves bearing saline water from the dissolved carbonate as observed by . In addition to the cave, the topsoil and vadose zones are also very marked on all ERT cross-sections. Results showed that ERT is the most suitable technique for mapping the karts systems in Mambaí and areas with similar hydrogeological conditions.

Results of seismic refraction show a clear three layer sub-surface stratigrahpy, where a contentious increasing trend in velocity is observed which is an indication of the depth wise increase in material compaction with depths. The method remained unable to delineate cave (30m deep) because of depth of penetration because limited acquisition profile lengths.

On VLF-EM results current density cross-sections of real component show a high resistivity anomaly at the beginning of profile which may possibly be associated with presence of subsurface dry cavity. These results are consistent with the ERT results. The length of VLF profiles were much longer than ERT so the high resistivity anomalies are also found in the surrounding area.

Based on the findings of the present study following improvements are suggested for the future works on the area.

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References

Nogueira, P. V., Rocha, M. P., Borges, W. R., Seimetz, E. X., & Cavalcanti, M. M. (2014). Comparison Between Results of Seismic Refraction and Standard Penetration Test (SPT) to Study Shallow Geological Subsurface in An Urban Area of Brasilia, Brazil. Revista Brasileira de Geofísica, 32(4), 673-679.

Brixová, B., Mosná, A., & Putiška, R. (2018). Applications of shallow seismic refraction measurements in the Western Carpathians (Slovakia): case studies. Contributions to Geophysics and Geodesy, 48(1), 1-21. RELEXW

Pereira, D. L., Galvão, P., Lucon, T., & Fujaco, M. A. (2019). Adapting the EPIK method to Brazilian Hydro (geo) logical context of the São Miguel watershed to assess karstic aquifer vulnerability to contamination. Journal of South American Earth Sciences, 90, 191-203.

Oladotun, A. O., Oluwagbemi, J. E., Lola, A. M., Maxwell, O., & Sayo, A. (2019). Predicting dynamic geotechnical parameters in near surface coastal environment. Cogent Engineering, (just-accepted).

Sundararajan, N., Al-Wardi, M., & Raef*, A. (2015, March). INTEGRATION OF MICRO-GRAVITY AND VERY LOW FREQUENCY (VLF) ELECTROMAGNETIC (EM) DATA ANALYSES TO OUTLINE HAZARDOUS CAVITIES AND LOW ROCK-STRENGTH: COASTAL CARBONATES, WADI SHAB, OMAN. In Symposium on the Application of Geophysics to Engineering and Environmental Problems 2015 (pp. 147-152). Society of Exploration Geophysicists and Environment and Engineering Geophysical Society.

Garcia, G. P., & Grohmann, C. H. (2019). DEM-based geomorphological mapping and landforms characterization of a tropical karst environment in southeastern Brazil. Journal of South American Earth Sciences, 93, 14-22.

Brandi, I., Sebastião, C. S., Ferreira, M. L., Lima, H. M. D., & Gama, M. F. P. (2019). Physical stability of iron ore caves: geomechanical studies of a shallow underground cave in SE Brazil. REM-International Engineering Journal, 72(2), 217-225.

dos Santos, E. S., Silva, R. W., & Sampaio, E. E. (2012). Analysis of the risk of karst collapse in Lapão, Bahia, Brazil. Exploration Geophysics, 43(3), 198-212.

de Queiroz Salles, L., Galvão, P., Leal, L. R. B., de Araujo Pereira, R. G. F., da Purificação, C. G. C., & Laureano, F. V. (2018). Evaluation of susceptibility for terrain collapse and subsidence in karst areas, municipality of Iraquara, Chapada Diamantina (BA), Brazil. Environmental earth sciences, 77(16), 593.

M. Gambetta, E. Armadillo, C. Carmisciano, P. Stefanelli, L. Cocchi, and F. C. Tontini (2011) Determining geophysical properties of a near surface cave through integrated microgravity vertical gradient and electrical resistivity tomography measurements. Journal of Cave and Karst Studies, v. 73, no. 1, p. 11–15.

Youssef, A. M., Al-Harbi, H. M., Gutiérrez, F., Zabramwi, Y. A., Bulkhi, A. B., Zahrani, S. A., ... & El-Haddad, B. A. (2016). Natural and human-induced sinkhole hazards in Saudi Arabia: distribution, investigation, causes and impacts. Hydrogeology Journal, 24(3), 625-644.

Akpan, A. E., Ekwok, S. E., Ebong, E. D., George, A. M. & Okwueze, E. E. (2018). Coupled geophysical characterization of shallow fluvio-clastic sediments in Agwagune, southeastern Nigeria. Journal of African Earth Sciences, 143, 67-7.

Mohamed, A. M. E., El Hussain, I., Deif, A., Araffa, S. A. S., Mansour, K., & Al Rawas, G. 2019 Integrated GPR, ERT and MASW for detecting near surface caverns at Duqm area, Sultanate of Oman. *Near Surface Geophysics*.

Elawadi, E., El-Qady, G., Nigm, A., Shaaban, F., & Ushijima, K. (2006). Integrated geophysical survey for site investigation at a new dwelling area, Egypt. *Journal of Environmental & Engineering Geophysics*, *11*(4), 249-259.

Chalikakis, K., Plagnes, V., Guerin, R., Valois, R., & Bosch, F. P. (2011). Contribution of geophysical methods to karst-system exploration: an overview. Hydrogeology Journal, 19(6), 1169.

Abbas, A. M., Khalil, M. A., Massoud, U., Santos, F. M., Mesbah, H. A., Lethy, A., ... & El Said, A. R. (2012). The implementation of multi-task geophysical survey to locate Cleopatra tomb at tap-Osiris Magna, Borg El-Arab, Alexandria, Egypt “phase II”. NRIAG Journal of Astronomy and Geophysics, 1(1), 1-11.

Krawczyk, C. M., Polom, U., Trabs, S., Dahm, T. (2012). Sinkholes in the city of Hamburg-New urban shear-wave reflection seismic system enables high-resolution imaging of subrosion structures. Journal of Applied Geophysics, 78, 133-143.

Abidi, A., Demehati, A., Banouni, H., & El Qandil, M. (2018). The Importance of Underground Cavities Detection in the Choice of Constructible Areas: Case of the Agglomeration of Fez (Morocco).

Basheer, A. A., Atya, M. A., Shokri, M., & Abu shady, M. M. (2012). Application of ERT and SSR to detect the subsurface cave at 15th May City, Helwan, Egypt. NRIAG Journal of Astronomy and Geophysics, 1(1), 23-32.

Stepisnik, U., 2008, The application of electrical resistivity imaging in collapse doline floors: Divaca karst, Slovenia: Studia Geomorphologica Carpatho-Balcanica, 12, 41–51.

DC. Ford, PW. Williams: Karst geomorphology and hydrology. Chapman and Hall, New York, 601p. (2007).

Ramesh Babu, V., Ram, S., & Sundararajan, N. (2007). Modeling and inversion of magnetic and VLF-EM data with an application to basement fractures: A case study from Raigarh, India. *Geophysics*, *72*(5), B133-B140.

Al-Tarazi, E., Abu Rajab, J., Al-Naqa, A., & El-Waheidi, M. (2008). *Detecting leachate plumes and groundwater pollution at Ruseifa municipal landfill utilizing VLF-EM method. Journal of Applied Geophysics, 65(3-4), 121–131.*

Al-Oufi, A., Mustafa, H. A., Al-Tarazi, E., & Abu Rajab, J. (2008). *Exploration of the extension of two lava tubes, faults and dikes using very low frequency-electromagnetic technique in NE Jordan. Acta Geophysica, 56(2), 466–484.*

Dindi, E. (2015). An assessment of the performance of the geophysical methods as a tool for the detection of zones of potential subsidence in the area southwest of Nakuru town, Kenya. *Environmental earth sciences*, *73*(7), 3643-3653.

McClymont A., Bauman P., Johnson E., Pankratow L., 2016: Geophysical Applications to Construction Engineering Projects. CSEG Recorder, 41, 4.

Prekopová M., Janočko J., Budinský V., Friedmanová M., 2016: Integration of seismic and sedimentological methods for analysis of Quaternary alluvial depositional systems. Environ. Earth Sci. 2017) 76:25.

Shahrukh M., Soupios P., Papadopoulos N., Sarris A., 2012: Geophysical investigations at the Istron archaeological site, eastern Crete, Greece using seismic refraction and electrical resistivity tomography. Journal of Geophysics and Engineering, 9, 6, 749–760.

Lapenna, V., Lorenzo, P., Perrone, A., Piscitelli, S., Rizzo, E. and Sdao, F. (2005). 2D electrical resistivity imaging of some complex landslides in Lucanian Apennine chain, southern Italy. Geophysics. 70, no. 3, B11-B18.

Colangelo, G., Lapenna, V., Loperte, A., Perrone, A. and Telesca, L. (2008). 2D electrical resistivity tomographies for investigating recent activation landslides in Basilicata Region (Southern Italy). Annals of Geophysics, 51(1), 275-285.

Loke, M.H. (2004). Tutorial: 2-D and 3-D electrical imaging surveys. Geotomo Software.

Sasaki, Y. (1992), Resolution of resistivity tomography inferred from numerical simulation: Geophysical Prospecting. **54**, 453–464.

Azwin, I. N., Saad, R., & Nordiana, M. (2013). Applying the seismic refraction tomography for site characterization. *APCBEE procedia*, *5*, 227-231.

dos Santos, E. S., Silva, R. W., & Sampaio, E. E. (2012). Analysis of the risk of karst collapse in Lapão, Bahia, Brazil. *Exploration Geophysics*, *43*(3), 198-212.

dos Santos, E. S., Sampaio, E. E., & Mocitaíba, L. D. S. (2013, August). Análise de Dados Gravimétricos, Magnéticos e de VLF aplicados ao estudo de Ferro na região de Lage-BA. In *13th International Congress of the Brazilian Geophysical Society & EXPOGEF, Rio de Janeiro, Brazil, 26–29 August 2013* (pp. 726-728). Society of Exploration Geophysicists and Brazilian Geophysical Society.

LOBO, H. A. S., BICHUETTE, M. E., HARDT, R., de Souza MARTINELLI, R., BRUNO FILHO, F. G., GALLÃO, J. E., ... & CALVO, E. M. CARACTERIZAÇÃO AMBIENTAL PRELIMINAR E PROPOSTA DE CONSERVAÇÃO DO SISTEMA CÁRSTICO DA GRUNA DA TARIMBA–MAMBAÍ, GO. *Application of Seismic Refraction TomoAN AIS do 33o*

Congresso Brasileiro de Espeleologia Eldorado SP, 15-19 de julho de 2015 – Sociedade Brasileira de Espeleologiagraphy in Karst Terrane

Shebl, S., Gemail, K. S., Attwa, M., Soliman, S. A., Azab, A., & Farag, M. H. (2019). Utilizing shallow seismic refraction in defining the geotechnical properties of the foundation materials: A case study at New Minia City, Nile Valley, Egypt. Egyptian Journal of Petroleum, 28(2), 145-154.

Attwa, M., & El-Shinawi, A. (2017). An integrative approach for preliminary environmental engineering investigations amidst reclaiming desert-land: a case study at East Nile Delta, Egypt. Environmental Earth Sciences, 76(8), 304.

Strelec, S., Mesec, J., Grabar, K., & Jug, J. (2017). Implementation of in-situ and geophysical investigation methods (ERT & MASW) with the purpose to determine 2D profile of landslide. Acta Montanistica Slovaca, 22(4), 345.

Brock-Hon et al. 2019 Geomorphic and geophysical evidence of a collapse origin for large sandstone depressions atop the western Cumberland Plateau in Tennessee.

Sundararajan, N., M. Narasimhachary, G. Nandakumar, and Y. Srinivas, 2007, VES and VLF an application to ground water exploration, Khammam, India: The Leading Edge, 708–716.