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The utility of geophysical techniques to image the shallow subsurface in karst areas in Missouri

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THE UTILITY OF GEOPHYSICAL TECHNIQUES TO IMAGE THE SHALLOW SUBSURFACE IN KARST AREAS IN MISSOURI

by

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This dissertation consists of the following articles, formatted in the style used by the Missouri University of Science and Technology:

Paper I, Pages 3-23, is entitled "Locating Unmarked Graves: Utilizing GPR and TDEM in Strickfaden-Cemetery, Missouri", as submitted to *FastTIMES* on May 23, 2018.

Paper II, pages 24-40, is entitled "Application of Multi-Channel Analysis of Surface Waves Method to Determine Optimum Parameter Settings in Karst Terrain in Southwest Missouri", was published in *International Journal of Science and Research* in volume 7, issue 1 (January, 2018).

Paper III, pages 41-53, is entitled "Mapping Bedrock in Karst Terrain with the Use of Electrical Resistivity Tomography and Multi-Channel Analysis of Surface Waves. A case study in Southwest Missouri", was published in *The Professional Geologist* volume 5, issue 1 (Jan, Feb, and Mar, 2018).

ABSTRACT

This dissertation is composed of three papers, which are focused on the utility of geophysical techniques to imaging the shallow subsurface in karst areas in Missouri.

In the first paper, ground penetrating radar (GPR) and time domain electromagnetic metal detector (TDEM-MD) methods were effectively deployed in an investigation of the cemetery with the intent of locating unmarked graves. The outcome of this study is to expand the knowledge of GPR and TDEM-MD methods, to locate unmarked graves in cemeteries. The study concluded that the GPR method is superior than TDEM-MD to locate buried caskets in cemetery investigations.

In the second paper, optimum field parameters of multi-channel analysis of surface waves (MASW) method were investigated in karst terrain and constrained with electrical resistivity tomography (ERT) data interpretation. Determinations were made based on the comparative analysis of MASW and ERT data results. It is concluded that the use of MASW method in karst terrain with smaller array provides good quality data.

In the third paper, ERT and MASW methods were effectively used to map the bedrock of study area by using shear wave velocity and resistivity values. It was observed that the bedrock in some study areas was difficult to recognize, because of the dry soils or moist soils were intact with bedrock. The results of this study indicate that ERT and MASW methods are suitable for mapping bedrock in a karst environment.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

PAPER III

LIST OF TABLES

1. INTRODUCTION

Missouri is known as a karst state. Karst areas are known to have a unique set of geotechnical and environmental difficulties that affect land use. Regardless of whether karst structures are exposed, they pose serious threats to properties such as buildings, agricultural farmland, cemeteries, roads, and railways. Numerous engineering problems are believed to be connected with construction in karst environments, such as disastrous collapse of the ground surface or a slow unnoticeable subsidence, which among other things, could lead eventually to the collapse of buildings, the destruction of railways and roads due to subsidence, and dam failures.

Karst is terrain with a special landscape and distinctive hydrological system developed by dissolution of rocks, particularly carbonate rocks such as limestone and dolomite, made by enlarging fractures into underground conduits that can enlarge into caverns, and in some cases collapse to form sinkholes (Ford & Williams, 2007; Klimchouk et al. 2000; Palmer, 2007). Downward percolating water slowly dissolves the host rock creating a network of enlarged fractures, fissures, and bedding planes.

In the past two decades, non destructive testing (NDT) methods have been widely used for geotechnical, environmental, and archeological investigations since they are in-situ, rapid, non destructive, and accurate compared with the traditional drilling or laboratory testing methods. Based on overall value, accuracy, ease of use, and cost, the NDT methods, such as the multichannel analysis of surface wave (MASW), electrical resistivity tomography (ERT), ground penetrating radar (GPR), and time domain electromagnetic (TDEM), are widely used and promising techniques (Gucunski et al. 2013; Burden, L.I, 2013; Anderson et al. 2012.)

In this research, the objective was to find optimum parameter settings of MASW in karst terrain. The results of MASW data were constrained to ERT data interpretation. Comparative analysis of MASW and ERT data indicated to use a shorter array of the MASW method in karst terrain to acquire good quality data. The use of optimum MASW parameter settings will help to significantly reduce the data acquisition time while providing the engineers reliable and high quality data.

Another area of interest to this research was mapping bedrock in karst terrain with the use of ERT and MASW methods. Previous studies revealed that traditional mechanical methods are commonly used to measure the depth to bedrock. These methods include coring, augering, and excavation, but these methods are also fairly expensive and time consuming. The results of this study will help geotechnical and environmental engineers in planning, design, inspection, and finding geological hazards.

As a part of this research application of ground penetrating radar (GPR) and time domain electromagnetic metal detector (TDEM-MD) in an investigation of a cemetery in northwest Missouri to locate unmarked graves is discussed. With the passage of time in older cemeteries grave markers are moved or destroyed, and once those grave locations are lost there is no easy way to find them again. The location of graves is essential in order to protect cemeteries from development, to avoid old graves when digging new graves, and to preserve the history of the community. The results of this study are most beneficial for archeologist, and researchers that want to use non destructive methods effectively for cemeteries investigations.

PAPER

I. LOCATING UNMARKED GRAVES: UTILIZING GPR AND TDEM IN STRICKFADEN-CEMETERY, MISSOURI

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ABSTRACT

A detailed geophysical investigation was conducted at the Strickfaden Cemetery in central Missouri to locate unmarked graves. To accomplish this goal, two geophysical techniques, namely ground-penetrating radar and time domain electromagnetic (metal detector), were used to survey the study area. General information exists about the location of burials in the cemetery: there were many marked headstones. However, while other burials are recorded in literary sources, their precise locations are unknown. It appears some of the headstones have been lost or misplaced over time.

The results of this study are based on the interpretations of ground-penetrating radar and time domain electromagnetic data, 20 unmarked graves were identified in the Strickfaden Cemetery. The authors believe that out of the 20 unmarked graves, 14 were classified to be probable graves, and 6 were classified to be possible graves.

1. INTRODUCTION

Cemeteries are often described as an eternal resting place for the deceased. The identification of graves often becomes difficult as time passes, as grave markers have been removed or destroyed, cemetery plans are lost, or because graves were never marked (Conyers 2006; Lowry and Patch 2017). A cemetery offers insight into community history and development over time (Conyers, 2006; Powell, 2004). Once grave locations are lost, there is no easy way to locate them again. Locating graves is essential to protect cemeteries from development, to avoid old graves when citing new graves, and to preserve the history of the community (Lowry and Patch 2017).

In the last two decades, numerous studies had been conducted using different non-destructive testing methods to locate buried structures. Because of overall value, accuracy, ease of use, and cost-effectiveness, ground penetrating radar (GPR) and time domain electromagnetic metal detector (TDEM-MD) are two increasingly used techniques (Schultz, 2009; Nobes, 1999). Using GPR and TDEM-MD in cemeteries is relatively common practice, particularly in older cemeteries where often records of the interments and descendent communities can no longer identify burial locations of graves or the cemetery boundaries. In these cases, GPR and TDEM-MD results can be used to answer questions about the grave locations, number of graves, spatial organization of the cemetery, or even the depth of graves (Powell, K. 2004; Giddens, Jason C. 2011; Lowry and patch 2017).

Ground penetrating radar (GPR) is a non-destructive tool that uses electromagnetic (EM) energy to infiltrate a variety of subsurface materials. The GPR measures the magnitude and two-way travel time of reflections from the boundary of subsurface materials possessing different electric properties (Shin and Grivas, 2003). In recent years, GPR has proven to be an effective technology for cemetery investigation. GPR is capable of locating buried objects in the ground (e.g., caskets) by detecting reflections that are returned to a receiving antenna (Sarah and Patch, 2017). The magnitude of those reflections and their elapsed travel time are recorded to determine the depths of the objects.

Time-domain electromagnetic metal detector (TDEM-MD) is a technique used to locate buried ferrous and non-ferrous metals for environmental and archaeological investigation. TDEM-MD is based on the following principle: A steady current is applied to the transmitter loop for a sufficient time period to enable the turn-on transients in the subsurface to dissipate, establishing a static primary magnetic field (EPA, 1993). The current is then withdrawn over a given ramp time and, according to Faraday's Law, the rate of change of the primary magnetic field induces an electromotive force. These secondary, or eddy, currents flow, and decay as a circular eddy current ring at successively greater depths; the decay is analogous to the dissipation of a smoke ring and depends on the electrical structure in the vicinity of the measurement (EPA, 1993). The rate of change of the electrical field as a result of eddy current decay generates a secondary magnetic field whose magnetic flux over time is measured by the receiver coil (McNeill, 1980).

This paper focuses on a geophysical survey conducted at the family-owned Strickfaden Cemetery located in Cooper County, Missouri (Figure. 1). The Strickfaden Cemetery study site was investigated to locate unmarked graves. According to the owner, the cemetery has American Civil War era graves, as well as present day graves. At the time of the civil war, it was customary to bury the military dead in uniform and sometimes with weapons, such as muskets, bayonets, and sabers. Some graves in the cemetery were marked with uncarved stones. The owner believes the depth of graves is between 4 ft to 4.5 ft; the authors believe the detection of caskets is expected at a depth of 1.0 ft to 2.0 ft.

The height of average casket used in America is approximately 30 inches and 18-inch dirt buffer on top of the casket (or two feet of soil if the body is not enclosed in anything), so the depth of a grave as shallow as 4 ft to 4.5 ft (Matt Soniak, 2012).

1.1. SITE DESCRIPTION

The study area at Strickfaden Cemetery is located in Cooper County in central Missouri (Figure. 1). The total area of Strickfaden Cemetery study site is approximately 100 by 100 ft SN-EW, metal fence defines the boundary of Strickfaden Cemetery study site (Figure. 2). The study area soils are clay rich sand, the presence of clay makes it difficult for the GPR operation to reach higher than 4 ft depth of penetration.

2. THE BASIC CONCEPT OF TEST METHODS

2.1. GROUND PENETRATING RADAR (GPR)

Ground-penetrating radar (GPR) is a tool that operates by sending short pulses of electromagnetic (EM) energy into subsurface materials. The transmitted energy is reflected back from an object or interface that possesses different dielectric properties than the surrounding material (Figure 3a). The remaining energy then propagates further and gradually diminishes over time. The propagation of the EM signal is highly dependent on the dielectric permittivity and electrical conductivity of the material being tested. The dielectric permittivity controls the speed of the EM signal whereas the electrical conductivity determines signal attenuation. The GPR unit measures the amplitude and travel duration of the EM signal that has been reflected, which are functions of variations in dielectric properties.

Figure (3a) shows the basic GPR method, in this figure (Tx) indicates transmitting signal and (Rx) indicates reflecting signal (http://scantech.ie/scantech-gpr-terms-of-use.html).Figure (3b) shows the hyperbolic reflections from the upper surfaces of graves (caskets). (Steven D. Sheriff, Subsurface Imaging in Archaeology 2013).

2.2. TIME DOMAIN ELECTROMAGNETIC (TDEM)

The time-domain electromagnetic metal detector measures the duration of decay of an EM pulse induced by a transmitter in the subsurface (Charles L. Garrett, 2002). In time-domain EM (TDEM) instrumentation, the transmitter current, while still periodic, is a modified symmetrical square wave as shown in (Figure 4a). After every second quarter-period, the transmitter current is shown to reduce to zero for one quarter-period abruptly, whereupon it flows in the opposite direction (Figure 4a). Figure 4b shows that there are four receiver voltage transients generated during each complete period (one positive pulse plus one negative pulse) of transmitter current flow. However, measurement is made only of the two transients that occur when the transmitter current has just been shut off.

3. DATA ACQUISTION AND PROCESSING

3.1. DATA ACQUISTION

The GPR and TDEM-MD surveys were performed simultaneously at Strickfaden Cemetery study site on September 21, 2017. It took approximately 5 hours to conduct the GPR and TDEM-MD survey. GPR was used as the primary tool and TDEM-MD as a supplemental tool.

3.1.1. Visual Survey. For this study, a thorough visual inspection of the cemetery was performed before carrying out GPR and TDEM-MD survey. Obstacles in the form of trees and headstones were located and documented. Notes taken from the visual inspection survey were incorporated into drawings of the cemetery showing location, and type of the obstacle observed (Figure. 5). Because of these obstacles, some of the traverses were shifted and had multiple run during the data acquisition.

3.1.2. Ground Penetrating Radar Survey (GPR). In this study, GPR data were acquired across the cemetery along parallel traverses south-north using a GSSI SIR-3000 400 MHz ground-coupled antenna mounted on a compact hand-pushed cart (Figure. 6), the acquisition parameters employed were 24 scans/unit-ft, and 512 samples/scan. Based on the soil condition a dielectric constant of 10 was used. GPR data were collected along 32 traverses, the length of each traverse was between 95-97 feet, equally spaced with 3 feet south-north, except for some of the traverses as mentioned in (Table 1). Due to the existence of obstacles, some traverses were shifted to different spacing or had multiple runs separated by spacing (Figure. 5).

3.1.3. Time Domain Electromagnetic Survey (TDEM). The metal detector used for this study was EM61-MK2. The EM61-MK2 is a time domain metal detector manufactured by Geonics Limited, mounted on a hand-pushed cart to collect the electromagnetic data (Figure. 6). The EM61-MK2 consists of a coincident transmitter (Tx) and receiver (Rx) coil and a second receiver coil located 30 centimeters above the Tx/Rx coil. The Tx coil is energized by a pulse of current, and the Rx coils measure the response decay at fixed moments in time (Manual, EM61-MK2). TDEM data were collected along 30 traverses using the same field geometry as that of the GPR survey. Profiles 18 and 32 for this survey were skipped because of the existing obstacle of headstones.

4. DATA PROCESSING

4.1. GSSI RADAN-7

The GPR data were processed using RADAN 7 (GSSI, Radan 7 User’s Manual, 2007). Radan processing steps included zero time removal, background removal, and then the interactive interpretation of the data. Figures 7(a) and 7(b) show non-processed and processed GPR data for profile No. 1, respectively.

4.2. SURFER

The SURFER software was used to plot a grid map depicting anomaly locations of GPR and TDEM by importing the (x, y) coordinates of each anomaly. Figures 8 and 9 display the interpreted GPR and TDEM anomaly maps, respectively at the Strickfaden Cemetery study site.

4.3. SUPERPOSING GPR AND TDEM DATA

Anomalies found in GPR data were overlaid on TDEM data for correlation. Overlaying the two datasets on the map provides an efficient means for correlation of the anomalies. Figure 10 shows the overlaying of data sets on the map.

5. RESULTS AND DISCUSSION

5.1. DETECTING BURIAL ANOMALIES

The GPR and TDEM anomaly locations of the cemetery study site were identified. The anomalies were identified during data interpretation of GPR and TDEM profiles.

The GPR anomalies appear as hyperbolic diffractions from the top of caskets shown in Figure 11 (a) and 11 (b) (Barone, 2012, Fiedler, et al. 2009, Telford et al. 1990). Typically, the caskets were detected within a depth of 1.0 ft to 2.0 ft. The authors believe that the reflected signal received on GPR profiles were from the top of the casket or burial vault. The TDEM anomalies appear as peaks of secondary EM signal. The authors believe this is because the presence of metal feature as shown in Figures 12(a) and 12(b).

The authors believe that the secondary EM signals were probably created by metal features associated with weapons, such as muskets, bayonets, and sabers.

5.2. LOCATING GRAVES

The locations of unmarked graves in the cemetery were identified by inspecting the anomalies in the GPR and TDEM–MD data (Figure 13). The marked graves were identified by the visual inspections and the available information obtained by the cemetery owners. In Figure 14, solid black rectangles show the location of the marked graves. The interpreted unmarked graves are classified into two categories: most likely to have burials or less likely to have burials, characterized by a solid red and yellow rectangle respectively. There were 20 unmarked graves located, where 14 were most likely to be graves, and 6 were less likely to be graves (Figure 13).

6. CONCLUSIONS

The objective of this paper was to locate the unmarked graves in Strickfaden Cemetery study site. The GPR and TDEM–MD data were collected and interpreted to locate unmarked graves. More specifically: GPR and TDEM–MD data were used to locate a total of 20 unmarked graves. Out of the 20 unmarked graves, 14 were probably to be graves, and 6 were possibly to be graves. The depth to the top of caskets were detected at 1.0 to 2.0 ft.

ACKNOWLEDGMENTS

The authors would like to thank Shishay Kidanu and James Hayes for their help during data acquisition.

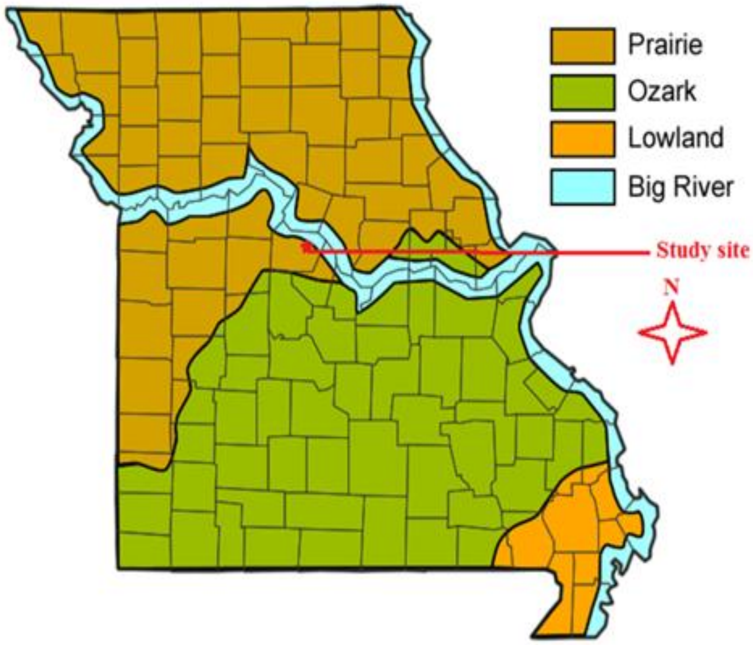
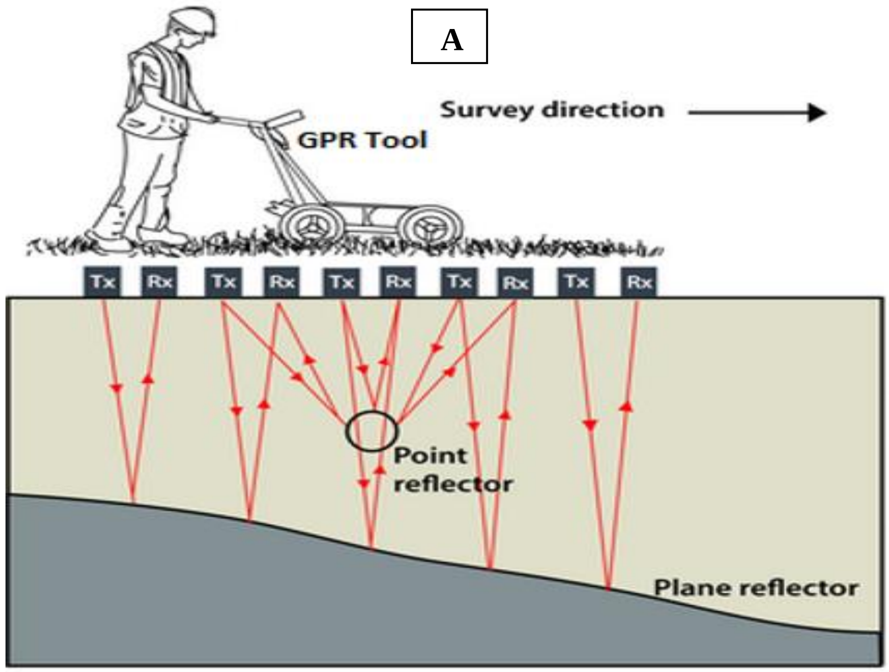


Figure 1. The location of Strickfaden Cemetery study site (Missouri Department of Conservation, 2018)

Figure 2. The location of Strickfaden Cemetery indicated with a red box (Google Earth, 2018)

A



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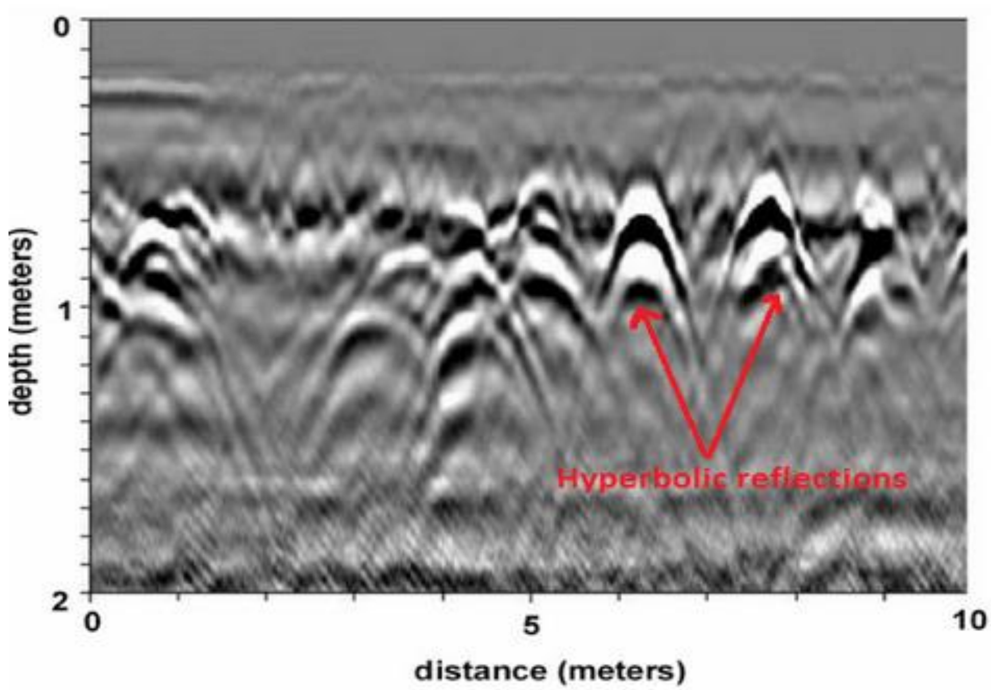
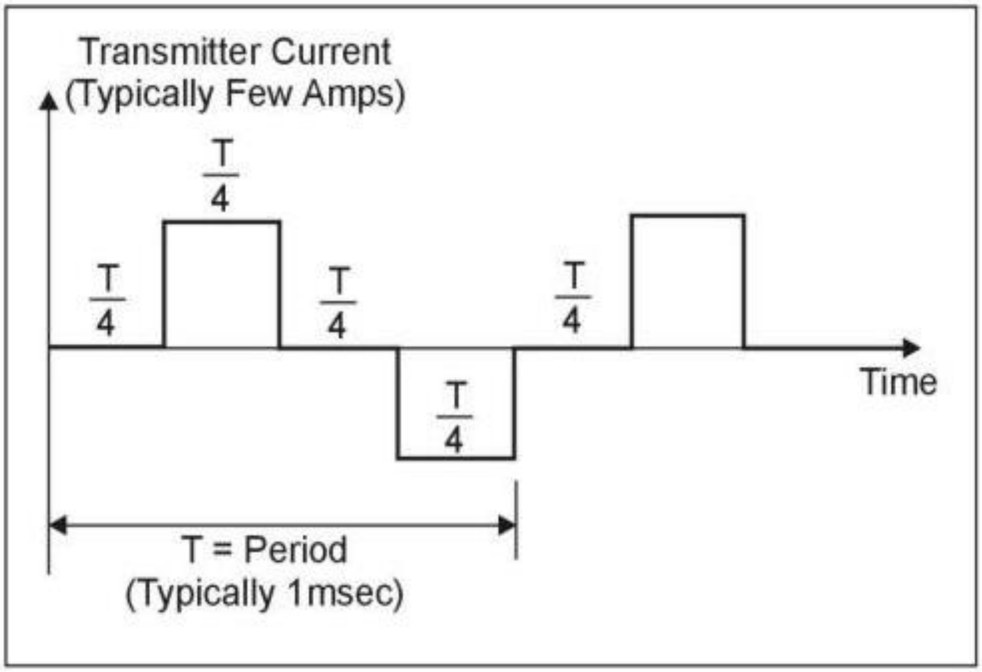


Figure 3. (a) A schematic illustration of GPR method; (b) Hyperbolic reflections from top of the casket

A



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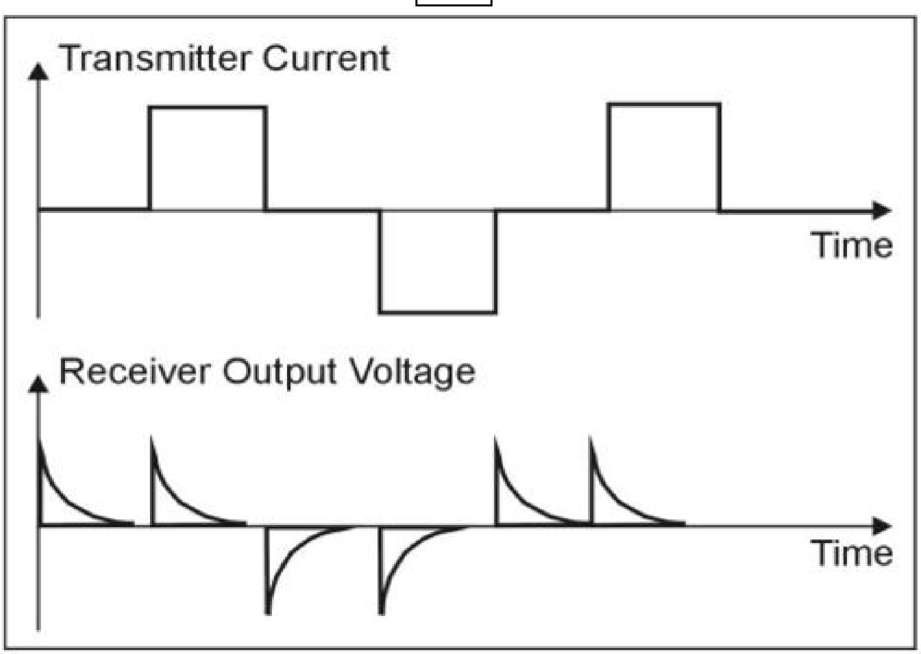


Figure 4. (a) Transmitter current wave form; (b) Receiver output wave form

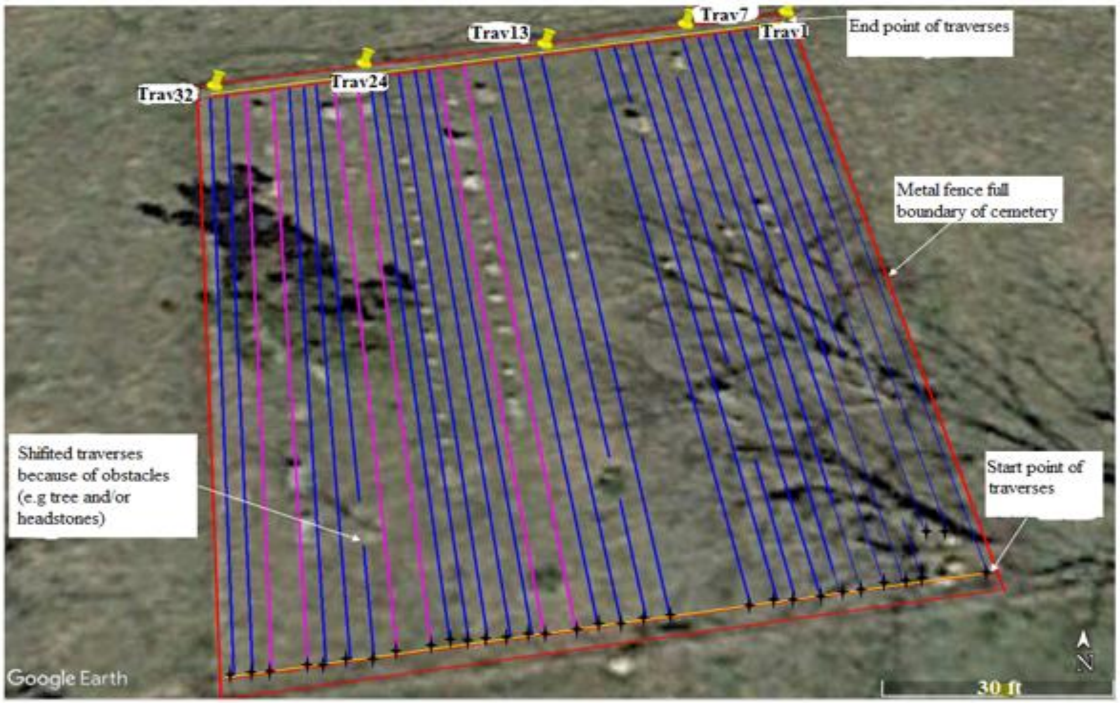
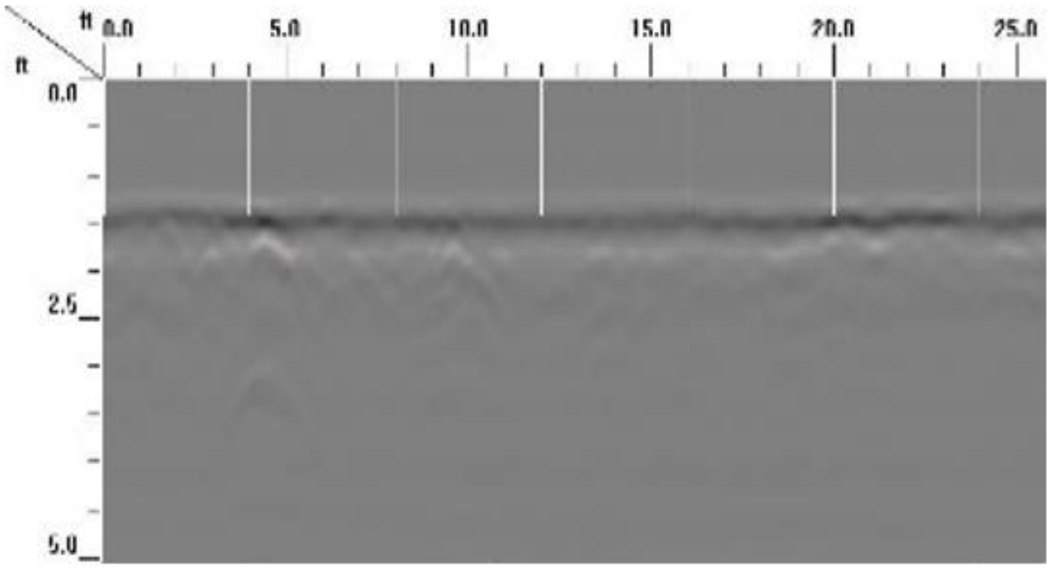


Figure 5. GPR and TDEM surveyed area line spacing layout

Figure 6. A photo of the field crew using GPR and TDEM tools

A



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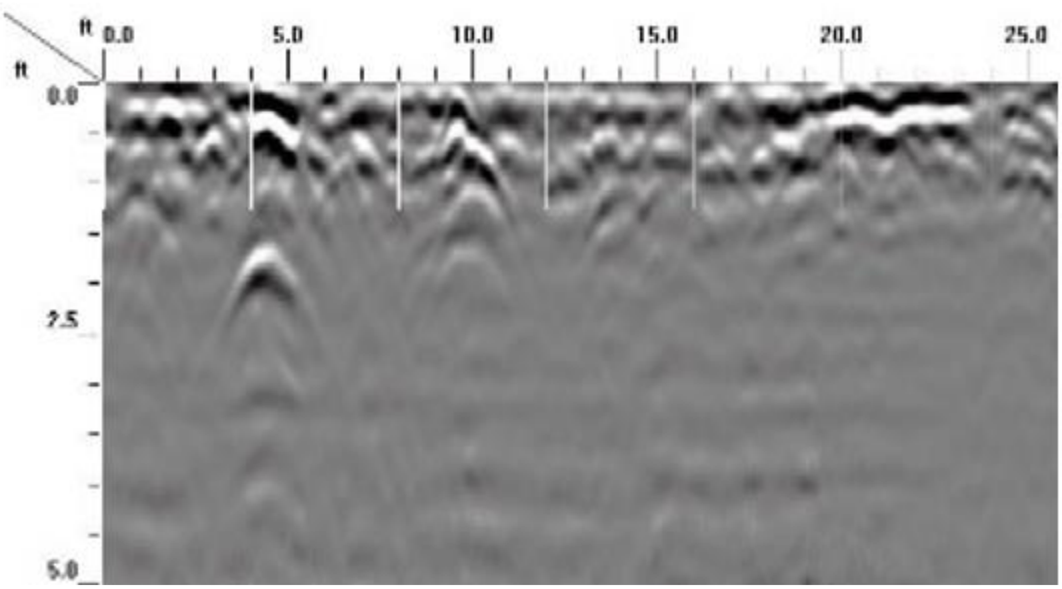

Figure 7. (a) Non-processed GPR data for Profile No. 1; (b) Processed GPR data for Profile No. 1

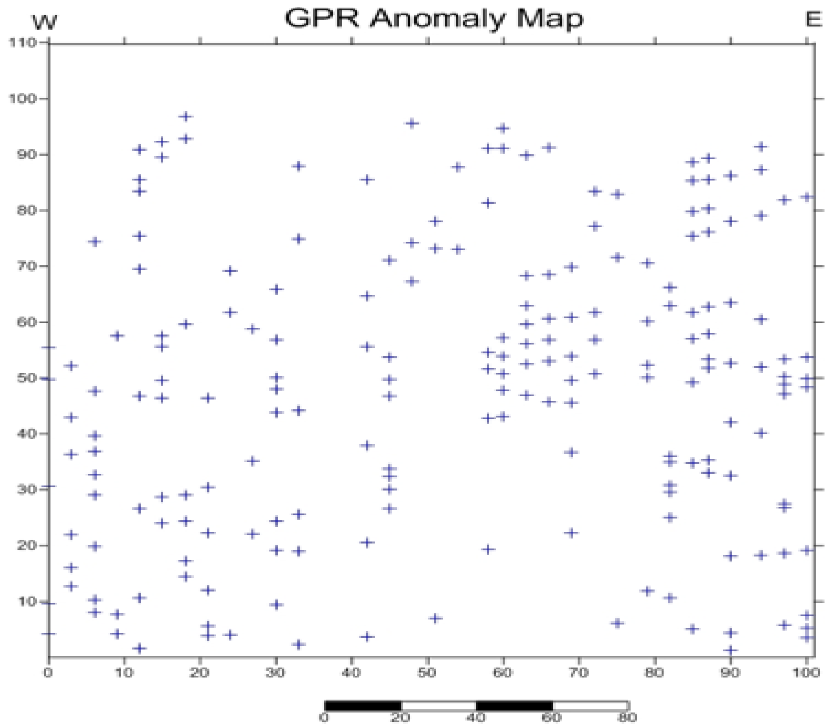

Figure 8. The GPR anomaly locations posted as blue crosses

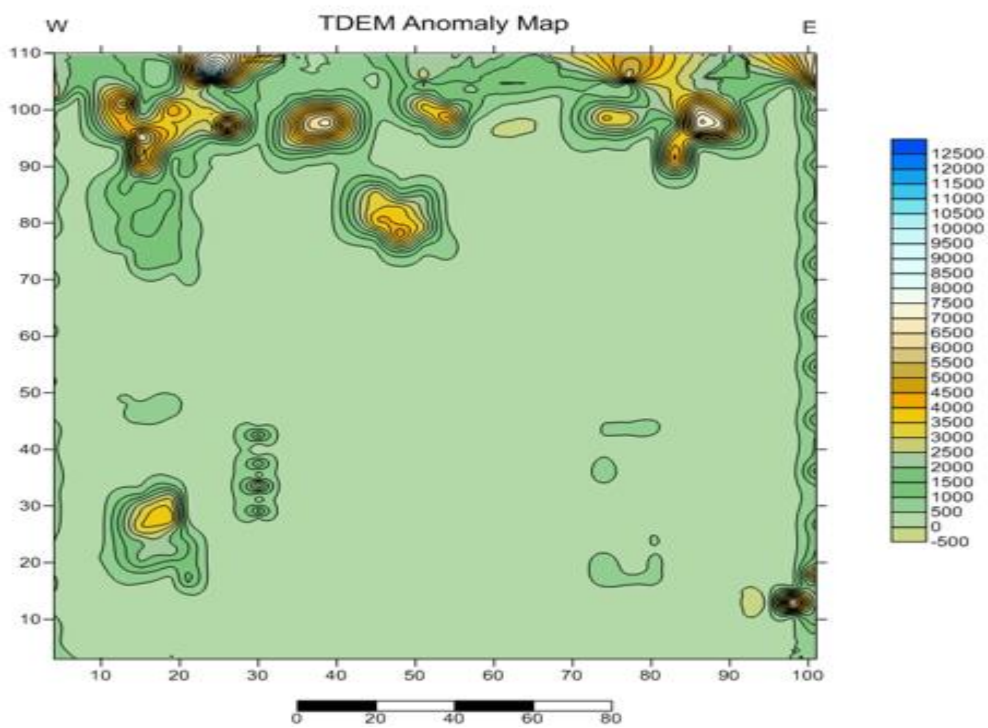

Figure 9. The TDEM anomaly map

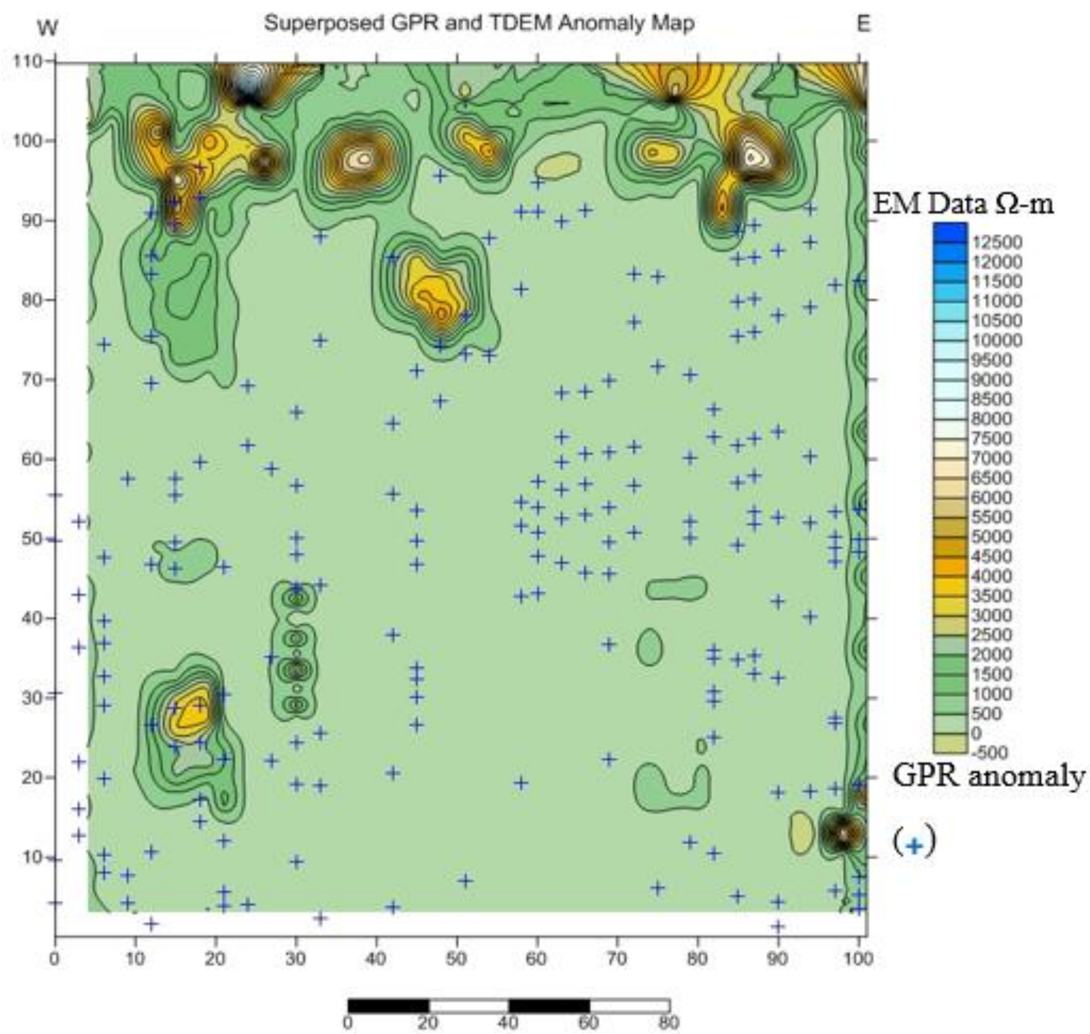

Figure 10. Superposed GPR and TDEM anomaly map

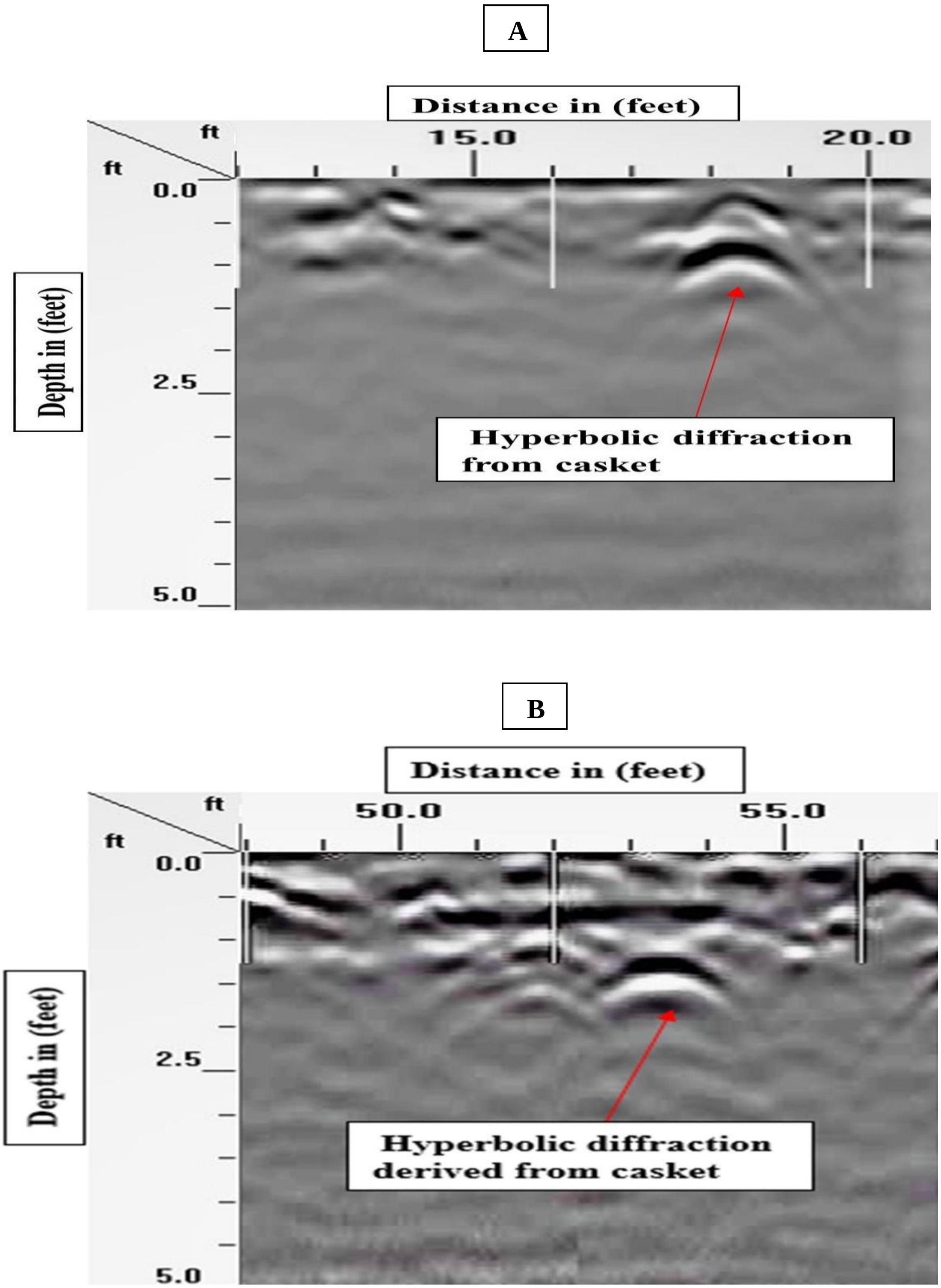

Figure 11. (a) Interpreted GPR data are showing an anomaly of burial in profile No. 31, as hyperbolic diffraction from top of a casket; (b) Interpreted GPR data are showing an anomaly of burial in profile No. 30, as hyperbolic diffraction from top of a casket

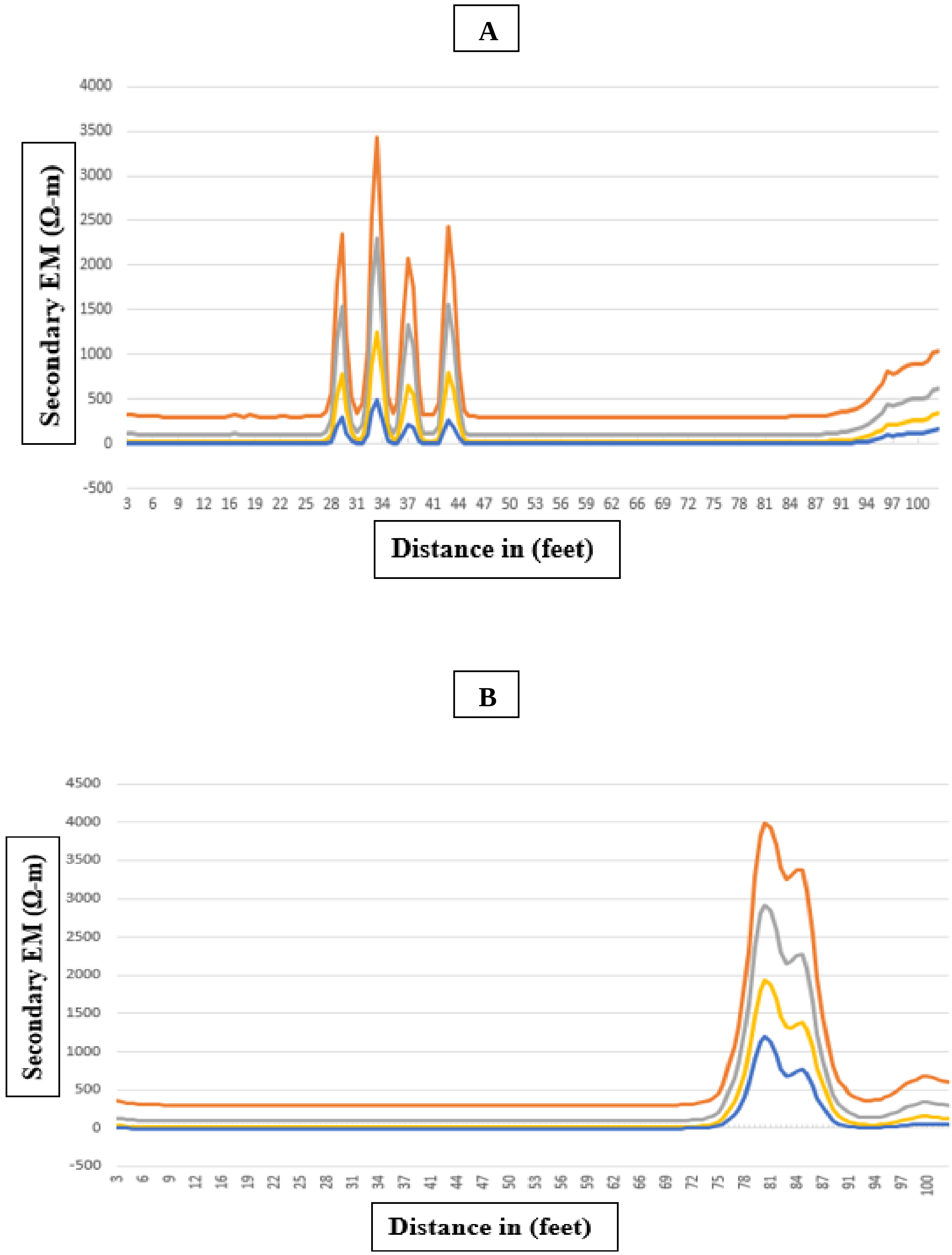

Figure 12. (a) Interpreted TDEM data are showing anomalies of burial in profiles No. 17, as peaks of secondary EM signal associated with the metal feature; (b) Interpreted TDEM data are showing anomalies of burial in profiles No. 22, as a peak of secondary EM signal associated with the metal feature

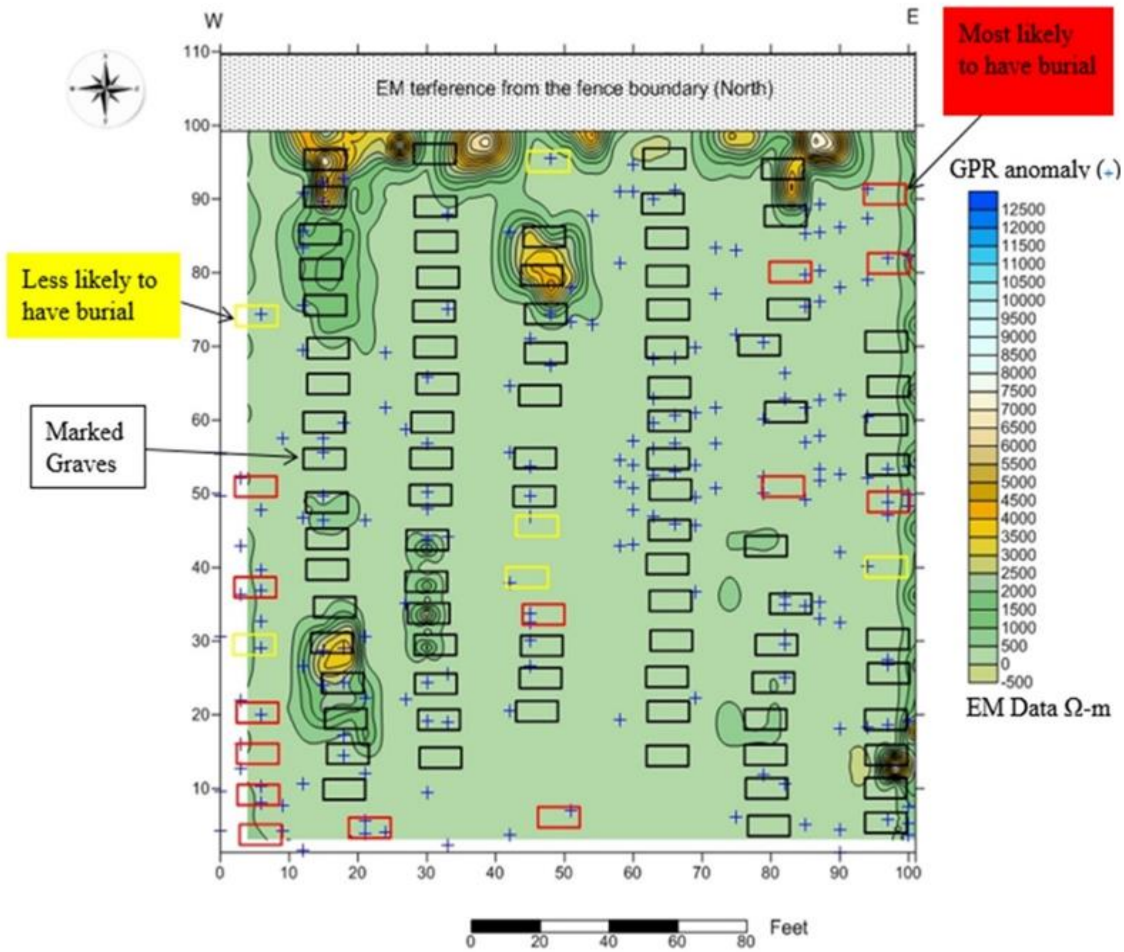

Figure 13. Superposed GPR and TDEM map showing the cemetery graves; marked graves with a black rectangle, red rectangles show the most likely burials while the less likely burials have marked with a yellow rectangle

Table 1. Traverses spacing interval

Traverses	**Spacing Interval (ft.)**
Traverse 12 and 13	9.0
Traverse 17 and 18	4.0
Traverse 18 and 19	2.0
Traverse 24 and 25	4.0
Traverse 27 and 28	2.0
Traverse 29 and 30	4.0

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II. APPLICATION OF MULTI-CHANNEL ANALYSIS OF SURFACE WAVES METHOD TO DETERMINE OPTIMUM PARAMETER SETTINGS IN KARST TERRAIN IN SOUTHWEST MISSOURI

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ABSTRACT

Active multi-channel analysis of surface waves data were acquired in karst areas in southwest Missouri to characterize the parameter settings of multi-channel analysis of surface waves. The quality of multi-channel analysis of surface waves data acquired were highly variable, because of the rapid lateral changes in karst enviornment. To verify the parameter settings of multi-channel analysis of surface waves, electrical resistivity tomography data were acquired, to superpose the multi-channel analysis of surface waves interpretations.

Electrical resistivity tomography data were acquired along east-west profiles at the study site to find the depth of bedrock. The multi-channel analysis of surface waves data were acquired at multiple locations along electrical resistivity tomography profiles. To confirm the accuracy of parameter settings, the authors made the depth of bedrock as a standard. This depth should have to be comparable to both multi-channel analysis of surface waves and electrical resistivity tomography data. The results of this study are based on the interpretation of multi-channel analysis of surface waves and electrical

resistivity tomography data. It is concluded that smaller geophones spacing and offset distance is recommended in karst terrain.

1. INTRODUCTION

Missouri is known as a karst state. Karst areas are identified to have a unique set of geotechnical and environmental difficulties that affect land use. The formation of karst terrain happens when a part of the sedimentary rock is dissipated by the act of groundwater. In Figure 1 the area shown is categorized by underground caves, fissures, and sinkholes. Karst is the most challenging environment regarding groundwater engineering and environmental issues (W. Zhou et al. 2002). The strength of soil is tremendously affected by continual drainage through karst soil subsoil; this changes the shape and size of karst voids. The variation in karst soil strength adds more problems for engineers in the building of various transportation infrastructure components (M. Dhital and S. Giri 1993, P. Gautam, S. Raj Pant, and H. Ando 2000).

Many geotechnical and environmental problems belong to land usage in karst areas (Thitimakorn et al. 2009). Whether karst structures are uncovered or not; the structures build on karst always remain under threat. These structures can be buildings, agricultural farmland, infrastructures, and railways. During construction, engineers understand the karst areas are associated with many engineering challenges, such as a dreadful failure of the ground surface or deliberate invisible subsidence. These failures can easily disturb the foundation system of the structures and eventually, collapse will occur due to subsidence. The area beneath the carbonate rocks tends to form large cavities that may lead to continuing ground subsidence, because of the gradual movement of fine grains from the subbase or to an uneven and pavement failure such as a sinkhole (Thitimakorn et al. 2009, Anderson et al. 2005, Ford and Williams, 2007). The electrical resistivity tomography (ERT) and multi-channel analysis of surface waves (MASW) methods are commonly used to investigate the shallow subsurface in the soil sciences, because of the progress in subsurface characterization in the field of geotechnical and environmental engineering. In recent decades the application of seismic methods like (MASW) is increased, due to the efficency and effectiveness for estimating ground velocity structures and mechanical properties of subsurface materials in variety of engineering field such as environmental, geological and geotechnical engineering,. (Lanz et al., 1998, Grandjean et al., 2007, Sturtevant et al., 2004).

MASW is a non-destructive method. The MASW technique makes use of elastic properties of surface waves for imaging the subsurface, while dispersive properties are utilized to attain shear wave velocity (Vs) profiles. The values of shear wave velocity (Vs) are directly correlated to the shear modulus, which attest how the soil will respond through dynamic loading. Karst features such as underground cavities, jointing, and subsidence massively affect the evaluation of the shear-wave velocity due to high signal-to-noise ratio (S/N). High S/N can be overcome during data acquisition and processing by proper arrangements of parameter seating; it plays a vital role in the quality of data.

Electrical resistivity tomography (ERT) is also a non–destructive method. The ERT method images and differentiates the lateral variations of the subsurface in the study area. It measures the voltages associated with an electric current flowing in the ground.

These currents are categorized in two types: natural currents or the currents introduced into the earth through electrodes.

This study was conducted to find the parameter settings of MASW in karst terrain in southwest Missouri. Using MASW in karst terrain is challenging because of the variable depth to bedrock and soil thickness. The objective of this study is to enhance the understanding of picking result–oriented parameter settings of MASW array in a karst environment.

1.1. STUDY AREA DESCRIPTION

The study site is located in Greene County close to the city of Springfield in southwest Missouri (Figure 2) and consists of two main physiographic regions: the Salem Plateau and Springfield Plateau. In particular the study area comes under the Springfield Plateau. The bedrock in this area is the Mississippian Burlington-Keokuk limestone, about 150 ft-270 ft thick. it is characterized by karstic features such as underground caves, losing streams, solution-widened joints, and sinkholes.

2. THE BASIC CONCEPT OF TEST METHODS

2.1. MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MASW)

The multi-channel analysis of surface aaves (MASW) is a sesmic method that uses surface wave (Rayleigh wave) energy to estimate shear wave velocities. A hammer or other acoustic source is used to generate a surface wave, and the geophones record the generated wave. The data acquired from the field is used to generate a dispersion curve (phase velocity versus frequency). The dispersion curve is then inverted and a 1-D shear wave velocity model is created. The Figure 3 shows the typical setup of MASW method.

2.2. ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

Electrical resistivity measurements are performed by passing an electrical current into the ground using multiple electrodes, and then measuring the resulting potiential difference within the subsurface. Typically, current (I) is transmitted and recievied between paired electrodes. The voltmeter electrodes are used to measure the potential differnce. Based on current (I), potential difference (ΔV) and electrode spacings, the resistivity (Δa) is calculated.

The depth of investigation and resolution is dependent on spacing between the current and potential electrodes (or both). The information on thickness of the layers within the subsuface is obtained by converting collected resitance data to model into apparent resistivity readings. Figure 4 shows a 2-D measurement configuration for a dipole-dipole array.

3. DATA ACQUISITION AND PROCESSING

3.1. DATA ACQUISITION

ERT data were acquired using an AGI R-8 SuperSting multi-channel and multi-electrode resistivity system with 168 electrodes spaced at 1.52 m (5 ft) intervals and using a dipole-dipole electrode array. The ERT profiles were acquired along four west–east oriented traverses spaced at 6.1 m (20 ft) intervals.

The multi-channel analysis of surface waves (MASW) data were acquired along west–east oriented ERT profiles at every 400 ft using twenty-four 4.5 Hz geophones spaced at 2.5 ft and 5 ft intervals, a 20 pound sledge hammer source, and an aluminum strike plate. Where necessary, MASW data acquisition locations were shifted because of access issues (ponded water, roadways, dense vegetation, etc).

3.2. DATA PROCESSING

Surfeis software package was used for the processing of MASW data developed by the Kansas Geological Survey. The first step of data processing is uploading the SEG-2 field records in Surfeis. Then these records are convereted into KGS format (Figure 6) to provide a flow chart for evaluating MASW profiles. The algorithms in the SurfSeis are used to assess each KGS file and define the properties, phase velocity and frequency of the surface wave and are used to draw descriptive dispersion curves (Park et al., 2009). Three steps have been performed to transfer field data to estimate shear wave velocity: first the field data were processed to obtain frequency and phase velocity of the surface wave for attaining the dispersion curves. Second the fundamental mode is recognized. Third the fundamental mode curve is inverted into an illustrative shear wave profile.

The AGI software RES2DINV and EarthImager 2D were used for data processing and inversion (Advanced Geosciences, Incorporated, 2009). To download and convert the field data into readable form, the RES2DINV and AGI EarthImager 2-D analysis software were used respectively. The apparent resistivity values can be interchanged into relevant psuedosection in the raw form. When the inversion process runs the EarthImager 2-D software using the measured apparent resistivity psuedosection to generate an earth model, the earth model fits the conductive characteristics of the recorded raw model. A flow chart in Figure 5 explains the ERT data inversion.

4. RESULTS AND DISCUSSION

The shear wave velocity (Vs) of MASW profiles were used to confirm the depth of bedrock. The accuracy of shear wave velocity (Vs) profile entirely relies on the generation of a decent quality dispersion curve, which is a significant step confronted during processing of surface wave data profiles. The excellent quality and accuracy of dispersion curves can be achieved through noise-free field data.

The results of two data sets with 2.5 ft geophone spacing and 10 ft offset distance are presented here to emphasize the salient features of MASW using a shorter array in karst. The results of MASW and ERT are then compared to confirm the accuracy of the results, the depth of bedrock is the standard; this depth should have to be comparable on both MASW and ERT data.

Figure 7(a) shows a dispersion curve, and figure 7(b) shows 10-layer velocity model. Only three layers were used in the interpretation of the shear wave velocity image. In Figure 7(b) the authors believe first-layer velocity (Vs) range is identified at 600-1000 ft/s. The soil thickness of this layer is 5-6 ft, followed by firm soil layer with velocity of 1000-1350 ft/s covering the depth 6-13 ft, and then the following layer with 1500 ft/s velocity corresponding with depth to top of bedrock. This depth to bedrock was confirmed through ERT interpreted profile in Figure 7(c). The results of MASW and ERT data interpretations are described in Table 1.

Similarly, the authors believe in the second data set of MASW, the velocity (Vs) range in the first layer is 1100-1300 ft/s with firm soil thickness of 6-7 ft, followed by the very soft soil (sand /silt) with velocity of 600-1200 ft/s covering the depth of 8-20 ft, and then the following layer with 1200-1700 ft/s velocity corresponding with depth to top of bedrock. This depth was confirmed by ERT interpreted profile in Figure 8(c). Figures 8(a) shows a dispersion curve, and 8(b) shows a 10-layer velocity model. Results of MASW and ERT interpretation are described in Table 2.

When the geophone spacing was increased to 5 ft, where MASW profile 1 and 2 were acquired, the estimated depth to the top of the bedrock was found at 26-ft. This depth to When the geophone spacing was increased to 5 ft, where MASW profile 1 and 2 were acquired, the estimated depth to the top of the bedrock was found at 26-ft. This depth to the top of the rock did not match with the ERT profile results. The depth found at these locations at ERT profile was 14 ft to 20 ft (Table 1 and Table 2).

In this study, the MASW data acquired with 5 ft geophones spacing cannot confirm the depth of bedrock on ERT profile. Therefore, these parameter settings are not recommended in a karst environment. An example of one data set with 5 ft geophone spacing is shown in Figure 9(a) and 9(b).

5. CONCLUSIONS

The conclusions of this study were drawn from comparative analysis of depth to bedrock on MASW and ERT. The optimum parameter settings of MASW method in karst terrain depends on three factors: the orientation of traverse, geophone spacing, and offset distance. In this study, the authors believe the depth of the top of the bedrock is 13-21 ft based on MASW interpreted data, which was acquired with 2.5 ft geophones spacing. The depth of top of the bedrock on ERT interpreted data profile is 14-20 ft, which is similar to the depth measure on MASW data. Typically, the users of MASW method recommend longer geophone spacing and offset distances for precise results. In contrast, in karst terrain, smaller geophone spacing and offset distances are recommended because of rapid lateral changes in depth to bedrock.

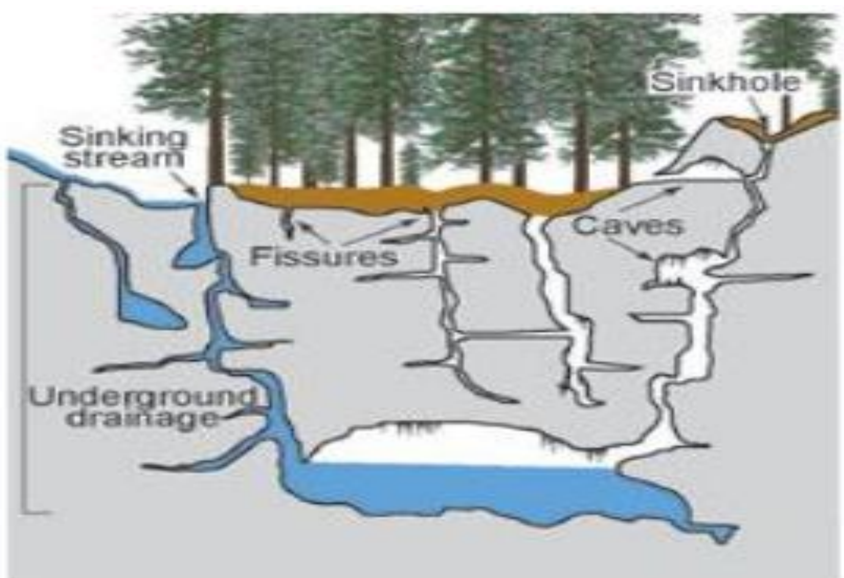

Figure 1. Formation of Karst Terrain (Environmental Science Institute2012)

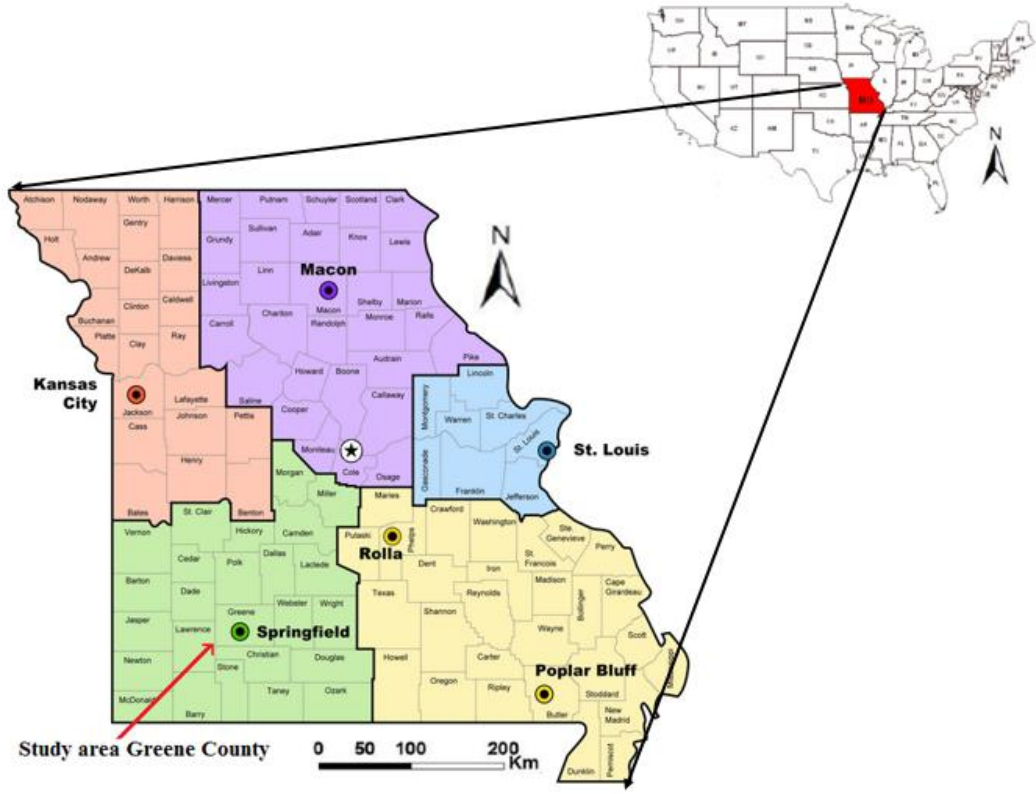

Figure 2. Location map of the study area in Greene County, Missouri

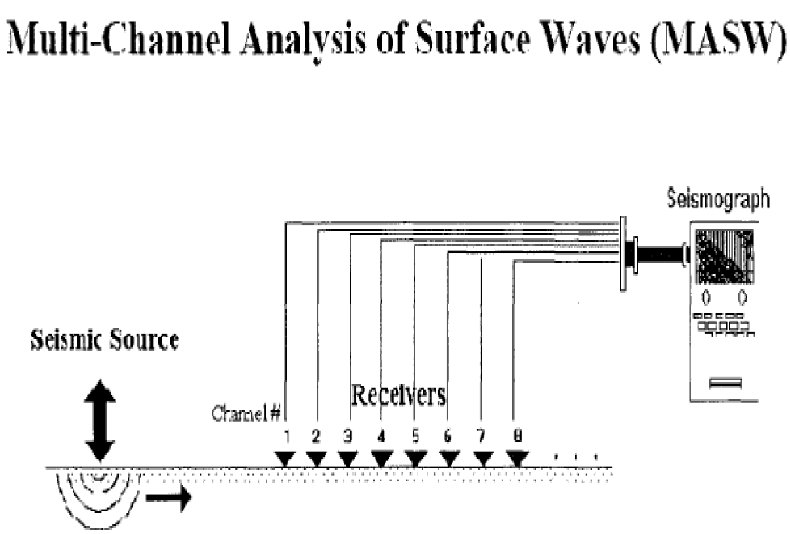

Figure 3. A schematic illustration of MASW method (Park et al, 1997)

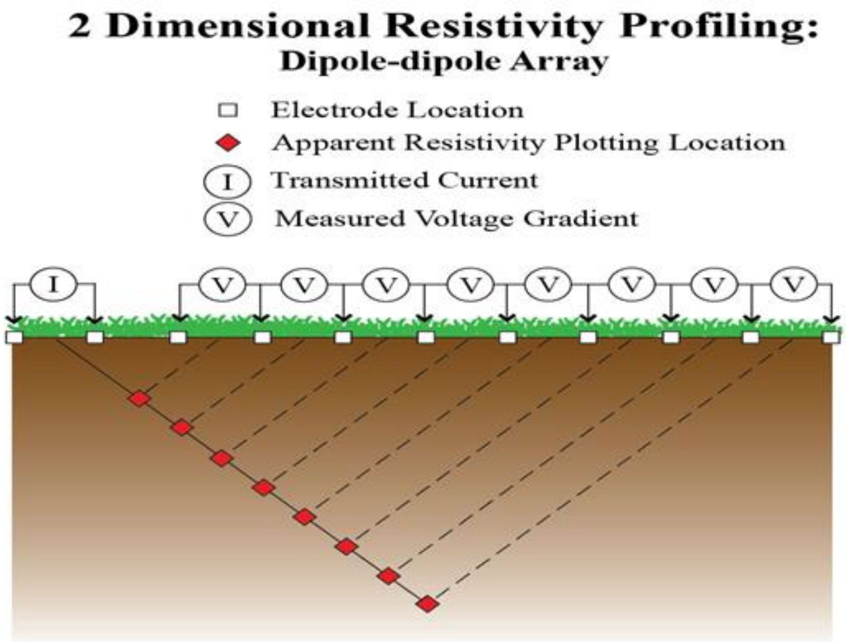

Figure 4. A typical dipole-dipole resistivity profile setup, red squares indicated the psuedosection plotting location (United States Environmental Protection Agency, 2014)

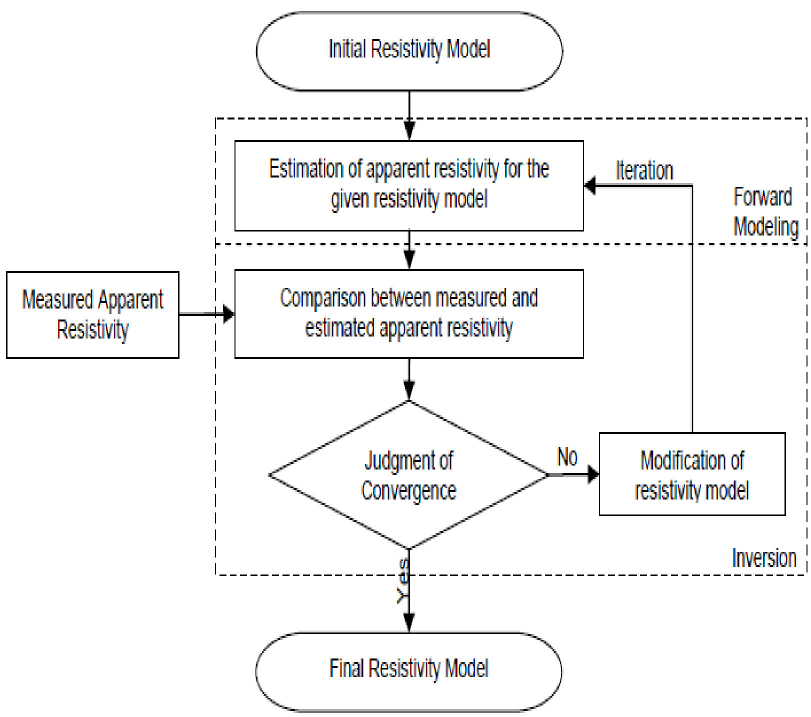

Figure 5. Flow chart describing the resistivity inversion process (Society of Exploration Geophysicist of Japan, 2004)

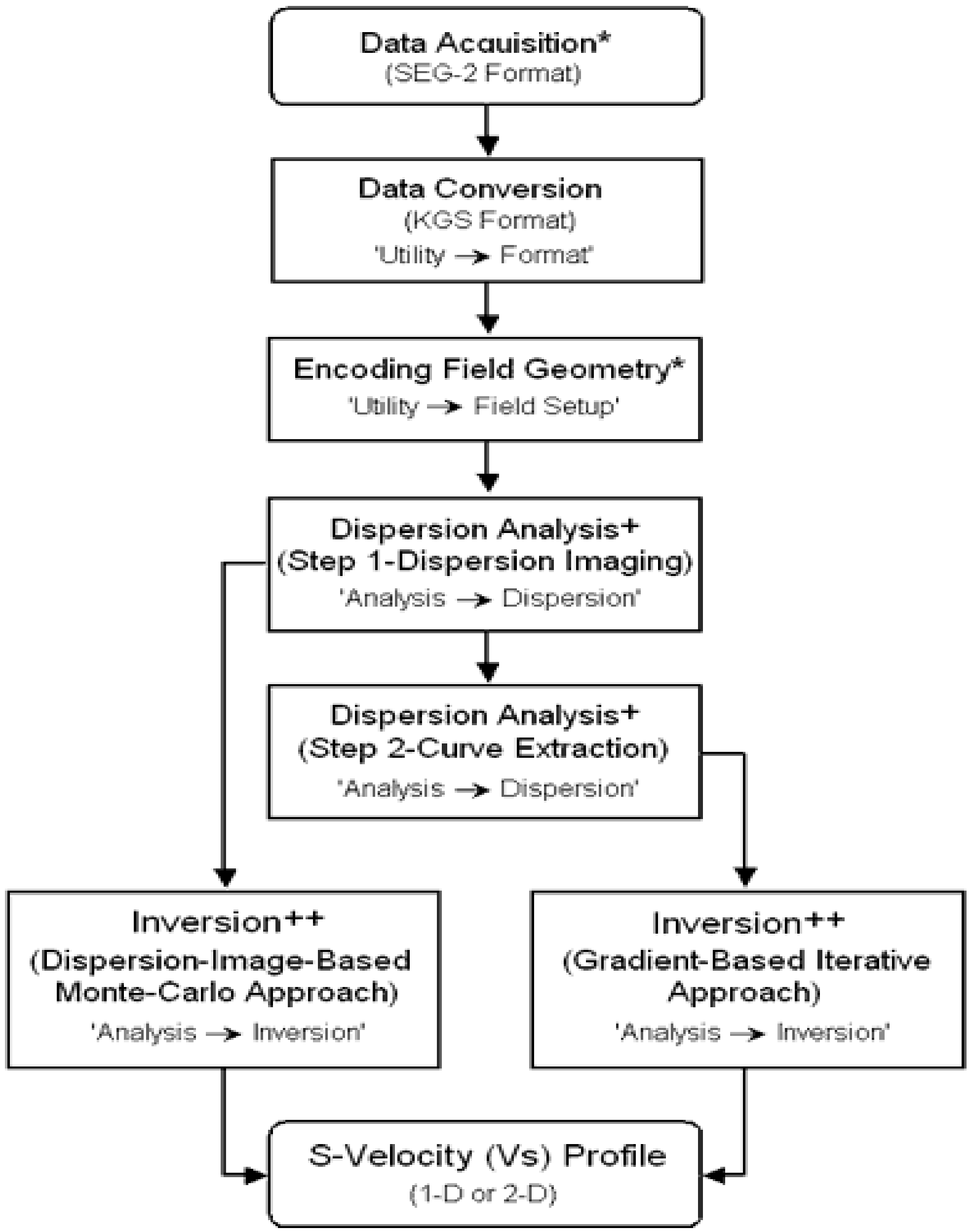

Figure 6. A step-by-step approach for data processing and analyzing MASW profiles (Kansas Geological Survey, 2014)

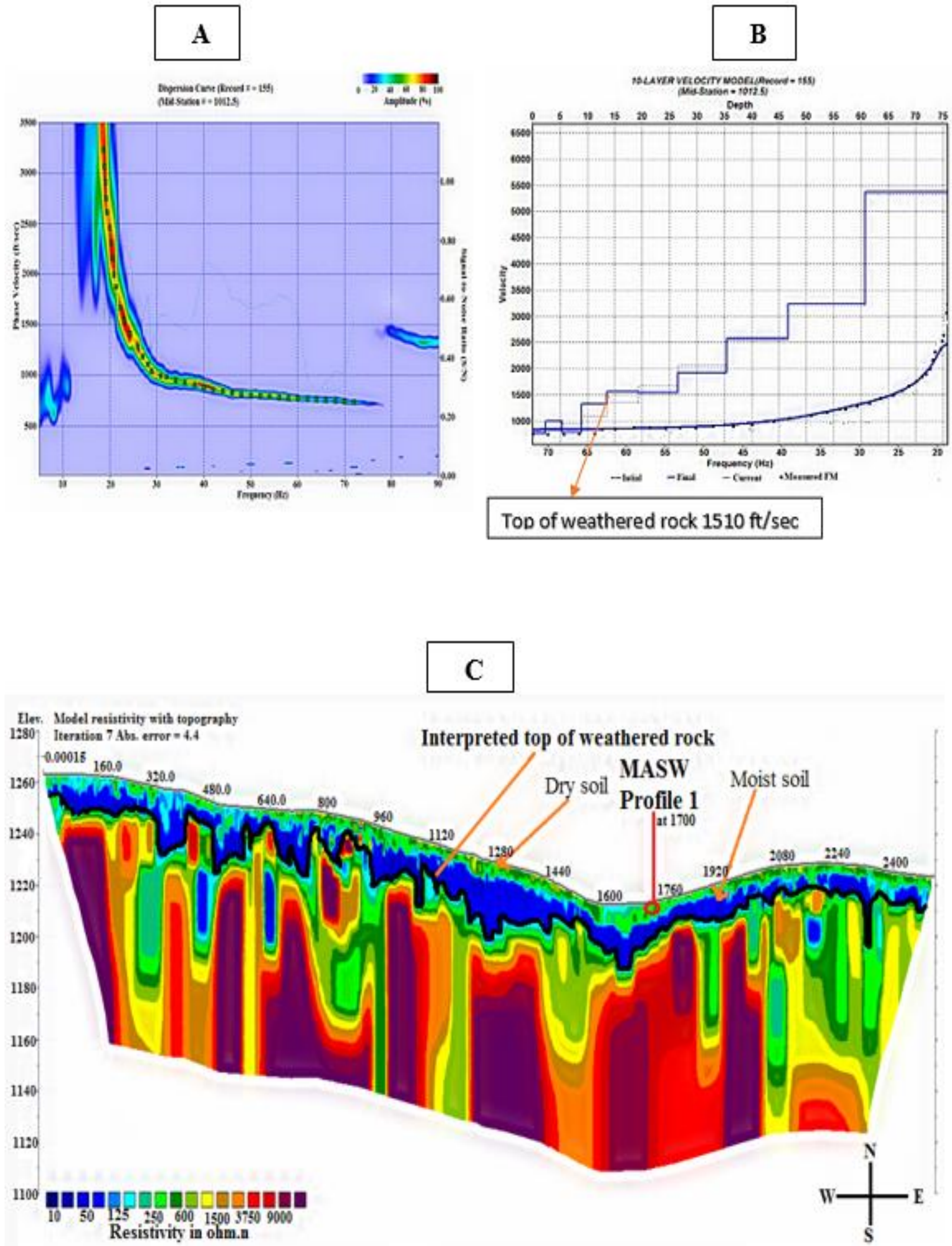

Figure 7. (a) MASW profile 1 dispersion curve (phase velocity versus frequency); (b) 1-D shear- wave velocity model of profile 1 (derived from dispersion curve); (c) ERT data profile along traverse trending east west

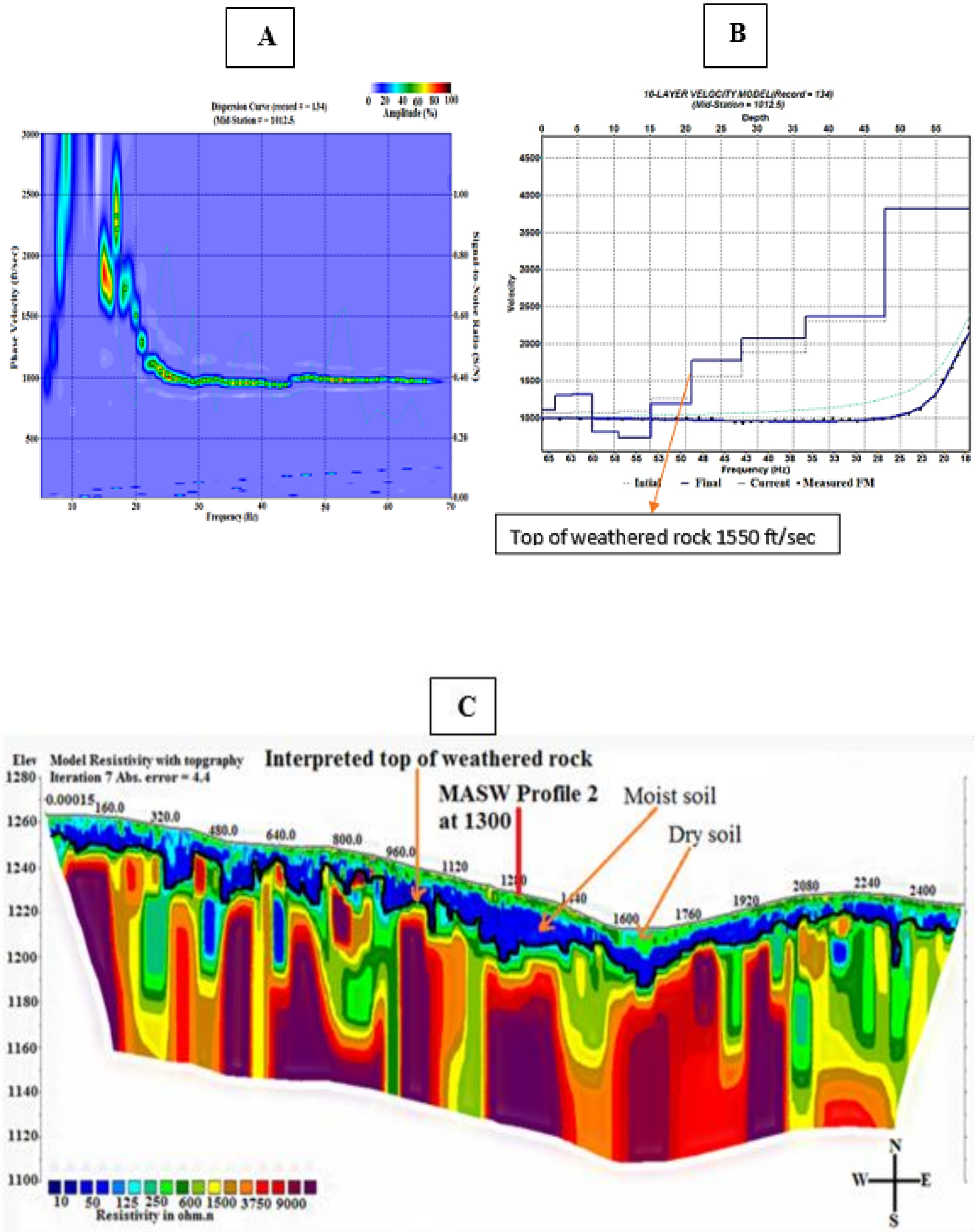

Figure 8. (a) MASW profile 2 dispersion curve (phase velocity versus frequency); (b) 1-D shear-wave velocity model of profile 1 (derived from dispersion curve); (c) ERT data profile along traverse trending east west

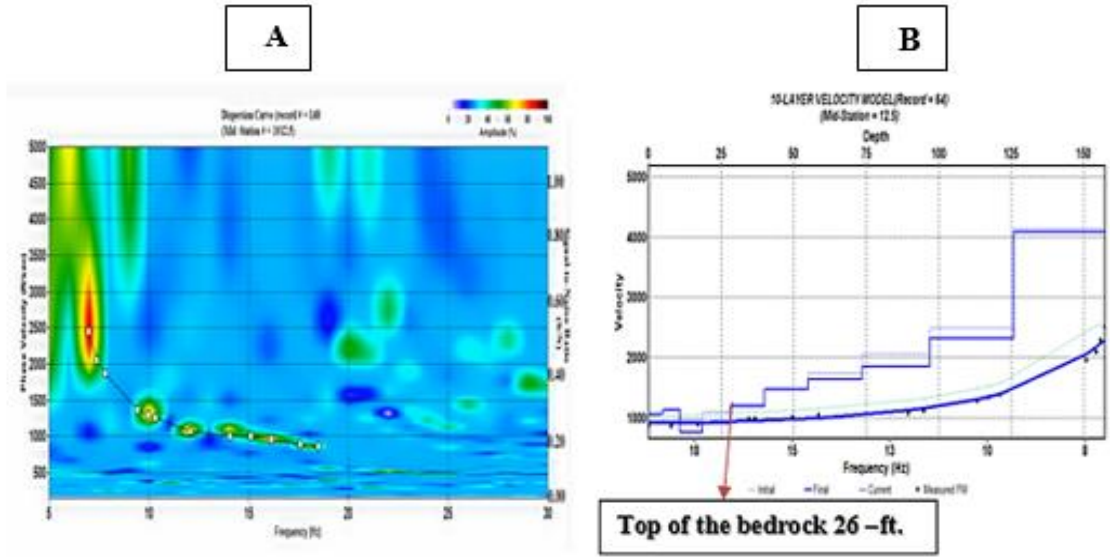

Figure 9. (a) MASW profile 3 dispersion curve (phase velocity versus frequency); (b) 1-D shear-wave velocity model

Table 1. Comparative analysis of MASW profile 1 and ERT

Profile 1	Depth to Top of Rock (feet)	Estimated Soil Velocity (feet/second)	Frequency Range (Hz)
MASW profile 1	13 (MASW-estimate of depth to the top of the rock)	1000	22-72
ERT (ties @ ~1700 feet mark)	14 (ERT-estimate of depth to the top of the rock)		

Table 2. Comparative analysis of MASW profile 2 and ERT

Profile 2	Depth to Top of Rock (feet)	Estimated Soil Velocity (feet/second)	Frequency Range (Hz)
MASW profile 2	21 (MASW-estimate of depth to the top of the rock)	1100	15-68
ERT (ties @ ~1300 feet mark)	20 (ERT-estimate of depth to the top of the rock)		

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III. MAPPING BEDROCK IN KARST TERRAIN WITH THE USE OF ELECTRICAL RESISTIVITY TOMOGRAPHY AND MULTI-CHANNEL ANALYSIS OF SURFACE WAVES. A CASE STUDY IN SOUTHWEST MISSOURI

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ABSTRACT

Electrical resistivity tomography (ERT) is a versatile, fast, and cost-effective technique for mapping the shallow subsurface bedrock. ERT covers a wide spectrum of resistivity, ranging from <1 Ohm.m to several thousands of Ohm.m. ERT data were acquired in karst areas in southwest Missouri with the objective of mapping the top of the rock. It was observed that the bedrock in some study areas was difficult to recognize, because of the same resistivity properties of bedrock and soils. To differentiate the soils from bedrock MASW method was used to image the shallow subsurface layers. Multi-channel analysis of surface waves (MASW) data were acquired along ERT traverses at different locations.

The results of this study are based on the comparative analysis of the MASW and ERT data. The bedrock characterization of the study site was divided into two groups: one group had resistivity values between 1000 and 1500 Ohm.m, indicating good rock quality, whereas the other group had values <250 Ohm.m, indicating unstable rock with

fewer water problems. From this investigation, the authors concluded that because of the overall value, accuracy, ease of use, and cost-effectiveness, ERT and MASW are very good methods for feasibility studies on mapping bedrock in karst.

1. **INTRODUCTION**

This case study is presented to illustrate how electrical resistivity tomography (ERT) can be used to accurately map the bedrock in karst terrain in Greene County, Missouri. Greene County, Missouri, is part of the Ozarks physiographic region and is known for its karst terrain. Karst terrain forms when a volume of sedimentary rock is dissolved by the action of groundwater (usually on limestone, dolomite, or marble), forming an area characterized by underground caves, fissures, and sinkholes, of which cover-collapse sinkholes are the most prevalent (Figure 1).

Missouri is widely known as “the state of caves.” There are several major karst areas found in Greene County. Karst is the most challenging environment in terms of groundwater engineering and environmental issues. Continual drainage through karst soil and subsoil changes the shape and size of karst voids and therefore significantly affects the strength of the soil itself. The strength variations of karst soils cause additional demands and concerns in the construction of various transportation infrastructure components. Therefore, picking a correct geophysical method of investigation plays an important role in the acquisition of useful results in karst topography.

Traditional mechanical methods are commonly used to measure the depth to bedrock. These methods include coring, augering, and excavation (Collins and Doolittle

1987). All of these methods are destructive, time consuming, expensive, and create a high level of soil disturbance (Collins & Doolittle 1987). In recent decades the electrical resistivity tomography (ERT) and multi-channel analysis of surface waves (MASW) methods are commonly used to investigate the shallow subsurface in many engineering fields such as environmental, geological, and geotechnical engineering (Lanz et al., 1998, Grandjean et al., 2007, Sturtevant et al., 2004). The use of these non-destructive, low cost, and more accessible methods are ideally required in karst terrain to estimate the depth of bedrock.

ERT is a non-destructive method. The ERT method is used to map top of the rock, identifying and characterizing potential karst. This method work by passing the electrical current into the subsurface by using a pair of electrodes made by copper or steel and then measuring the potential difference within the subsurface by using a second pair of electrodes.

MASW is a seismic method. This method is used to locate low velocity zones to identify karst features, large shallow voids, fracture/fault zones, and areas of cut and fill. The working principle of MASW is to use a hammer or other acoustic source to produce a surface wave. The low frequency geophones (4.5 Hz) used to record the propagation velocities of that wave. The data recorded at each shot point is used to generate dispersion curves during data processing. The phase velocity of the surface waves as a function of frequency is show, by the dispersion curves. Shear wave velocity (Vs) versus depth can be calculated in 1-D profiles from the dispersion curve.

In this study ERT and MASW techniques were employed together to map the estimated depth of bedrock in karst terrain in southwest Missouri. The objective of this study is to enhance the understanding of picking result–oriented parameter settings of MASW array in a karst environment. It is concluded in this investigation that the bedrock of the study site can be divided into two groups: the bedrock with resistivity values between 1000 and 1500 Ω m, indicating good rock quality, and values <250 Ω m indicating unstable rock.

1.1. STUDY AREA LOCATION AND GEOLOGY

The study site is located in southwest Missouri, close to the city of Springfield, Greene County (Figure 2). Bedrock in this study area is the Mississippian Burlington-Keokuk Limestone about 150-270 ft. thick, but varies in thickness because of erosion (Vandike 1993). Karst features are prevalent almost throughout Greene County (Figure 3). The solution process has extensively affected the Burlington-Keokuk Limestone, this resulting in the formation of numerous karst features: caves, springs, sinkholes, losing streams, cherty clay residuum, etc. (Shishay et al., 2016).

2. DATA ACQUISITION

2.1. ERT DATA

The ERT data was acquired along a traverse trending east-west to obtain a detailed subsurface coverage of the study area. A dipole-dipole array was selected due to the need for high lateral resolution. The total traverse length was 835 ft after measuring the required length, and 168 metal stakes were installed at 5 ft interval along the 835 ft traverse. Eight cables, each consisting of 21 electrodes, were spread along the array, and each electrode was attached to a metal stake (168 electrodes attached to 168 metal stakes). The metal stakes are made of steel, and a SuperSting R8 instrument was used to measure the resistivities.

2.2. MASW DATA

The MASW data were acquired at specific locations perpendicular to the ERT traverse. Data were acquired using twenty-four 4.5 Hz geophones spaced at 2.5 ft intervals, a 20 pound sledge hammer source, and an aluminum strike plate. Where necessary, MASW data acquisition locations were shifted because of access issues (ponded water, roadways, dense vegetation, etc.). The MASW data were acquired with the overarching goal of determining the engineering properties of the subsurface. Specific objectives included mapping variations in the depth to top of rock, mapping variations in soil thickness, determining the engineering properties of rock, determining the engineering properties of soil, and constraining the ERT interpretation (especially with respect to depth to top of rock).

3. DATA PROCESSING

The MASW data processing was performed using the SurfSeis software package, developed by the Kansas Geologic Survey. Processing began by uploading SEG-2 field records into SurfSeis, and then the records were processed and converted into KGS format. Algorithms in the SurfSeis routine were used to analyze each KGS file and determine surface wave phase velocity and frequency properties and to plot representative dispersion curves. Each shot record had a unique dispersion curve, and each curve had to be analyzed manually by the processor to identify and select best fit for the fundamental mode (Park et al., 2009).

The ERT data processing and inversion was performed using AGI Administrator software, which was used to download and convert field data into a form readable by the AGI EarthImager 2-D analysis software. In the raw form, measurements of apparent resistivity can be plotted onto the respective pseudosection. The EarthImager 2-D software uses the measured apparent resistivity pseudosection during the inversion process to recreate an earth model fitting the conductive characteristics of the recorded raw model (Advanced Geosciences, Incorporated, 2009).

4. RESULTS AND DISCUSSION

The interpreted bedrock is divided into two groups: resistivity values <250 Ωm indicate clay-bearing, unstable rock while resistivity values between 1000 and 1500 Ωm indicate good rock quality. Moist soil is characterized by resistivity values less than 125 Ωm and dry soil is greater than 125 Ωm. The interpreted top of weathered rock has been highlighted on a west–east oriented ERT profile (Figure 4A, 5A). The top of weathered rock on the ERT profile has been independently verified by MASW control (Figure 4B, 5B). The MASW array was centered at the 100 and 900 ft marks on the ERT Profile. As indicated in Table 1 and 2, the MASW “acoustic” top of rock as determined at the MASW test location along the ERT Profile is consistent with the top of rock as mapped at the corresponding 2-D ERT station location.

The results show that soil thicknesses on the ERT profile vary from approximately 10 to 25 ft. The overall shear-wave velocity of soil varies between 800 and 1200 ft/sec and averages about 1000 ft/sec. The velocity of intact rock varies between 2000 and 2900 ft/sec. Typically, thinner soils are characterized by higher average shear wave velocities (1100 ft/sec). Thicker soils are typically characterized by lower average shear velocities (800 ft/sec).

5. CONCLUSIONS

Traditional mechanical methods are commonly used to measure the depth to bedrock but results of this study proved that ERT and MASW are very good methods for mapping bedrock in karst terrain because of their overall value, accuracy, ease of use, and cost-effectiveness. It is concluded that estimated top of bedrock based on ERT and MASW data interpretations shows in range of 16 -19 ft. The bedrock of the study site is divided into two groups: resistivity values between 1000 and 1500 Ω m which indicate good rock quality, and values <250 Ω m which indicate unstable rock.

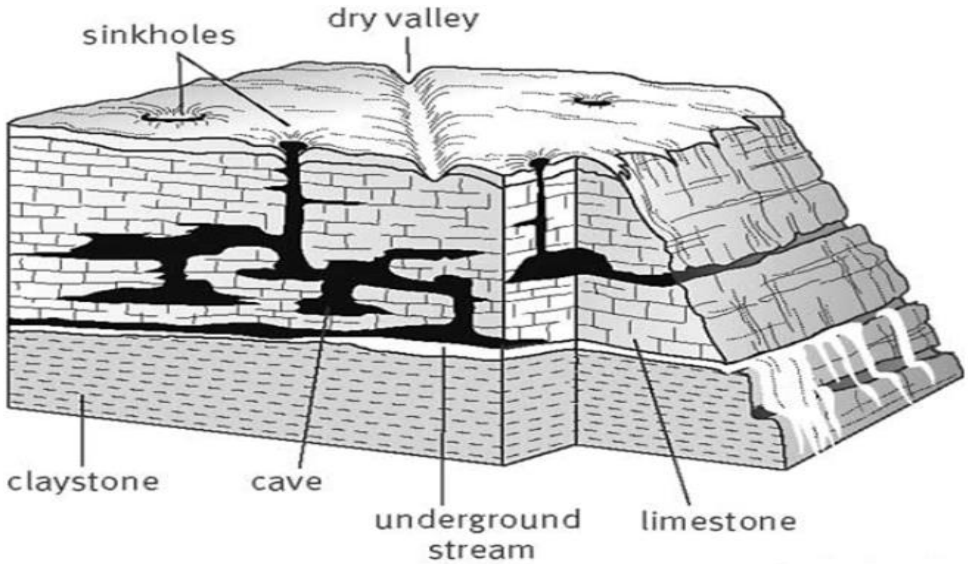

Figure 1. Karst Terrain diagram (Science Dictionary, 2017)

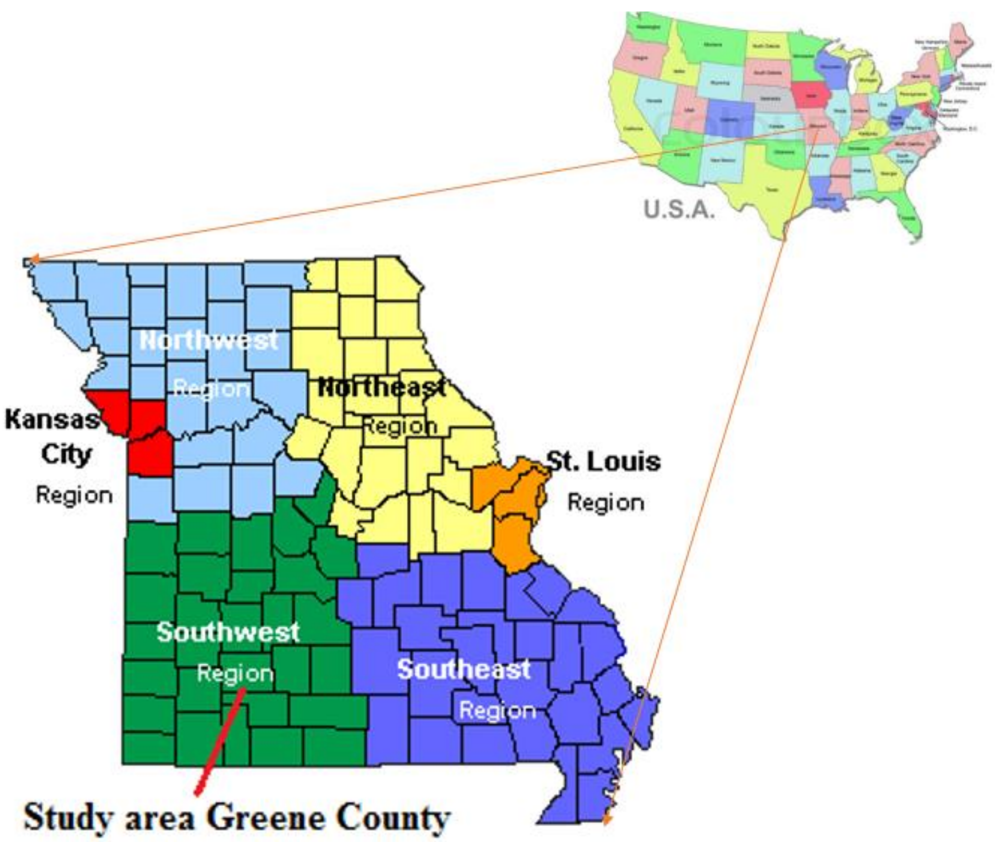

Figure 2. Location map of the study area in Greene County, Missouri

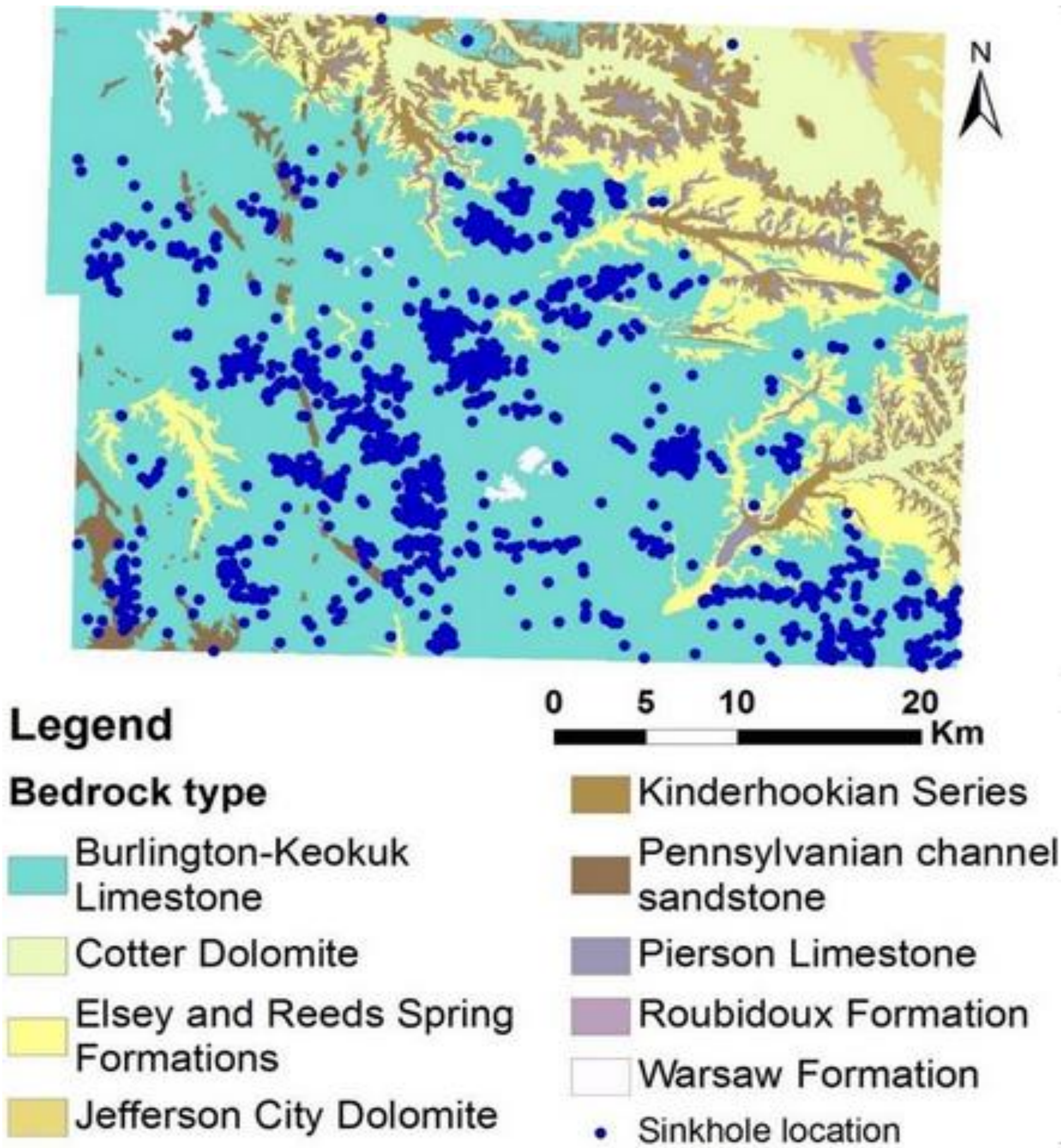

Figure 3. Geological map of Greene County, Missouri (Esri data source: Missouri Geological Survey GEOSTRAT, 2017)

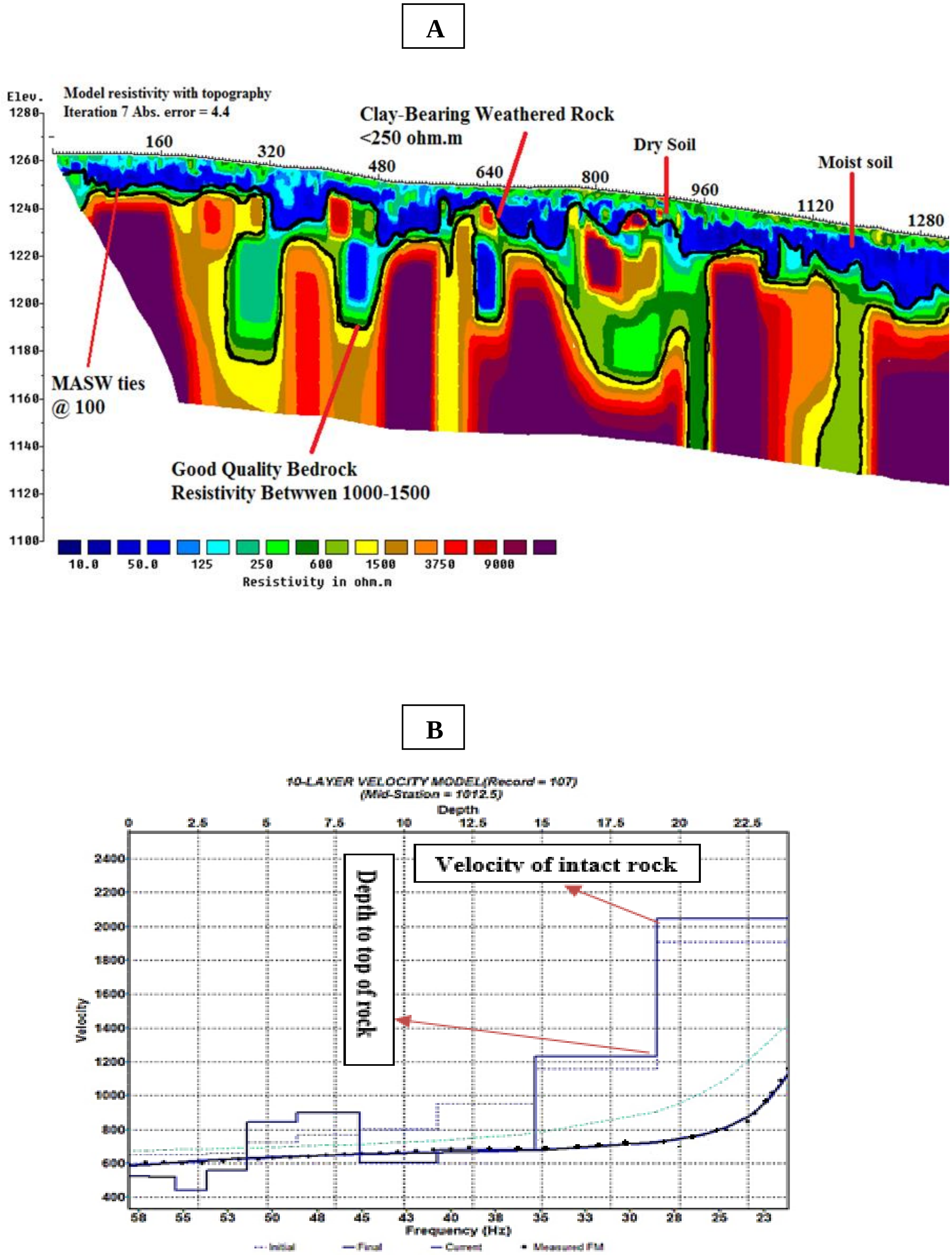

Figure 4. (a) Interpreted ERT profile; (b) 1-D shear wave velocity model profile 1

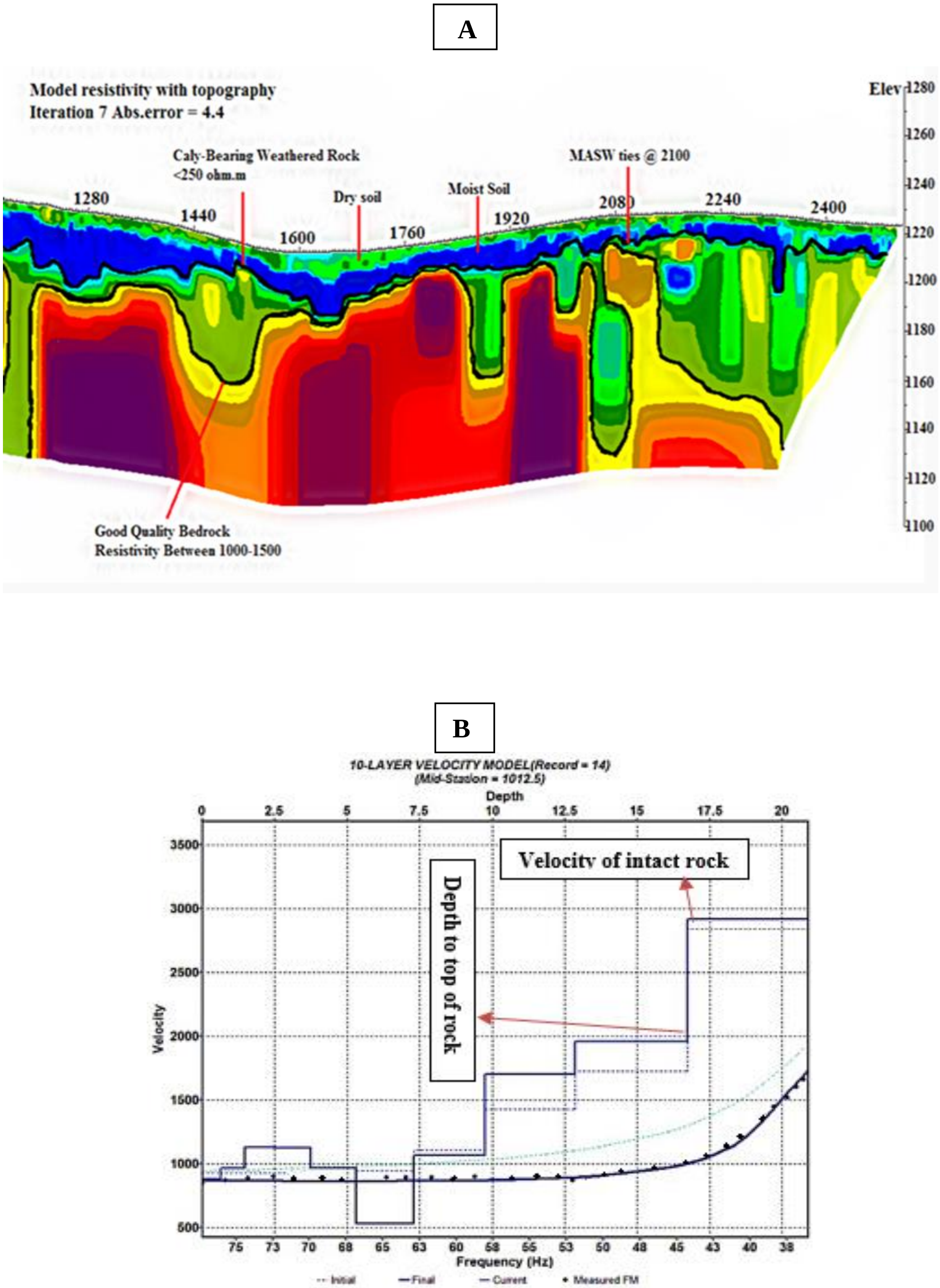

Figure 5. (a) Interpreted ERT profile; (b) 1-D shear wave velocity model profile 2

Table 1. Comparison of ERT and MASW profile 1 interpretations

Profile	Soil Thickness	Soil Velocity	Depth to Intact rock	Velocity of Intact rock
MASW	14 ft	900 ft/s	19 ft	>2050 ft/s
ERT ties @ 100 ft	13 ft		18 ft	

Table 2. Comparison of ERT and MASW profile 2 interpretations

Profile	Soil Thickness	Soil Velocity	Depth to Intact rock	Velocity of Intact rock
MASW	9 ft	1200 ft/s	16.5 ft	>2900 ft/s
ERT ties @ 2100 feet	11 ft		17 ft	

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SECTION

2. CONCLUSIONS

The first paper described the parameter settings of multi-channel analysis of surface waves (MASW) that can be used in karst environment. The confirmation of MASW parameter settings were achieved by comparing the electrical resistivity tomography (ERT) and MASW data. The main concern in using a MASW method in karst is that it needs significant amount of time and cost for data acquisition. Therefore appropriate parameter settings of MASW technique were offered in this study to reduce the time and cost. Qualitative and quantitative comparisons of data collected by ERT and MASW were performed in this study and recommended to use shorter array of MASW method in karst environment.

The second paper presented a successful implementation of two non destructive techniques (MASW and ERT) to map the depth to bedrock in karst terrain, instead of using mechanical methods (coring, augering and excavation). The use of ERT and MASW methods does not create soil disturbance, and data acquisition is cost-effective and fast. Because of the variable depth of bedrock in karst terrain, these non destructive methods are ideally required to estimate the depth of bedrock in karst.

The third paper presented an integrated approach to locate unmarked graves in Strickfaden Cemetery. Ground penetrating radar (GPR) and time domain electromagnetic (TDEM) were used to locate unmarked graves. The 16 unmarked graves were located after interpreting the GPR and TDEM anomalies. This study suggested using GPR and TDEM methods in old cemeteries to locate unmarked graves.

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VITA

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