NOVEL PROTOCOL OF ENGINEERING GEOPHYSICS IN URBAN ENVIRONMENTS

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NOVEL PROTOCOL OF ENGINEERING GEOPHYSICS IN URBAN ENVIRONMENTS

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LIST OF SYMBOLS

V	Voltage
R	Configuration resistance
I	Current
ρ	Resistivity
k	Geometric factor
G	Configuration factor
ε	Dielectric permittivity
ε_r	Relative dielectric permittivity
μ	Magnetic permeability
V_1	Potential energy of layer 1
V_2	Potential energy of layer 2
m^*_1	Electron no. 1 effective masses
m^*_2	Electron no. 2 effective masses
γ	Propagation constant
k	Wave number
v	Velocity
α	Attenuation constant
μ	Magnetic permeability
σ	Electrical conductivity
ω	Angular frequency = $2\pi f$
ε_R	Relative permittivity
β	Phase constant

LIST OF ABBREVIATIONS

2-D	Two dimensional
3-D	Three dimensional
C	Centre
CH	Chainage
CMP	Common-Midpoint
CSAMT	Controlled-Source Audiomagnetotellurics
CSL	Chan Sow Lin
CSMT	Controlled-Source Magnetotelluric
DSC	Differing Site Condition
EM	Electromagnetic
ERT	Electrical Resistivity Tomography
etc	Et cetera
IP	Induced Polarization
L	Left
PDP	Pole-dipole
PIS	Pre-Investigation Survey
POD	Propane-Oxygen Detonator
RSVP	Refraction Seismograph Velocity Profiling
R	Right
RF	Radio Frequency
S	Short
SWD	Seismic-While-Drilling
TBM	Tunnel Boring Machine
TEM	Transient Electromagnetic
TSWD	Tunnel-Seismic-While-Drilling
VHF	Very High Frequency
VLF	Very Low Frequency
W	Wenner
XRD	X-Ray Diffraction

PROTOKOL NOVEL GEOFIZIK KEJURUTERAAN DI PERSEKITARAN BANDAR

ABSTRAK

Kajian ini dilakukan di kawasan bandar dengan menumpukan kepada pengesanan dan pemetaan retakan, lowong, pengisian rongga, runtuhan rongga, “pinnacles” dan jerungkau yang selalu terjadi di kawasan batu kapur. Dalam kajian ini, kaedah geofizik pengimejan keberintangan 2-D digunakan. Kajian melibatkan rekabentuk kaedah pengambilan data yang baru (protokol) dengan menggunakan susunatur Wenner, Wenner-Schlumberger dan Pole-dipole bagi mendapatkan imej yang lebih baik, kedalaman yang lebih dalam dan kurang hingar. Protokol baru ini (RSWenner, RSWenner-Schlumberger and RSPole-dipole) diuji kemampuannya memeta ciri-ciri subpermukaan. Tiga model direka bagi mengkaji kesesuaian protokol baru; model menggunakan perisian RES2DMOD secara teori, model makmal dan model lapangan (bersaiz kecil) dalam medium asal. Kajian menunjukkan protokol RSPole-dipole dengan jarak elektrod yang sesuai merupakan yang terbaik untuk mengesan dan memetakan retakan, lowong dan muka batuan. Kawasan kajian adalah projek “Stormwater Management and Road Tunnel” (SMART) iaitu sepanjang Jalan Chan Sow Lin (penjajaran terowong), Kuala Lumpur. Kajian dibahagikan kepada dua bahagian iaitu pra-terowong dan post-terowong. Bagi kajian pra-terowong, maklumat lengkap subpermukaan sangat penting bagi menghindar pelbagai masalah dan kemalangan. Disebabkan kawasan kajian merupakan kawasan yang sibuk dengan kenderaan, kekurangan ruang dan masa yang terhad, tidak semua pencerapan data menggunakan protokol RSPole-dipole dapat digunakan. Sebahagian kajian digantikan dengan protokol RSWenner 32SX (L dan S). Semua data akan dikaitkan antara satu sama lain termasuk data lubang gerek. Kajian pra-terowong menunjukkan terdapat banyak kawasan lemah (retakan, lowong, pengisian rongga, runtuhan rongga) di sepanjang jajaran terowong SMART dengan kedalaman muka batuan adalah 1.25 – 10 meter. Kajian post-terowong bertujuan melihat kesan “grouting” dan “Tunnel Boring Machine” (TBM). Radar Penusukan Bumi (GPR) digunakan bagi memetakan utiliti dan ciri-ciri subpermukaan yang sangat cetek. Kajian GPR menunjukkan terdapat banyak utiliti pada subpermukaan.

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ABSTRACT

This research was carried out in an urban area and it was focused on detecting and mapping fractures, voids, filled cavities, collapsed cavities, pinnacles, cliff subsurface and overhangs that often occur in limestone areas. Prior to the field survey, the geophysical method, 2-D resistivity imaging was used and the research was to develop new resistivity acquisition techniques (protocols) that can provide better image; deeper penetration and less noise. The arrays used are Wenner, Wenner-Schlumberger and Pole-dipole. The new protocols (RSWenner, RSWenner-Schlumberger and RSPole-dipole) were tested for their ability to map the underground features. Three models were designed to study the suitability of the new protocols; a theoretical model using RES2DMOD software, a laboratory model and a field model (miniature) with original medium. The study shows that the RSPole-dipole protocol with proper electrode spacing is the best protocol used to detect and map cavities, fractures and rock head. The study area was at the Stormwater Management and Road Tunnel (SMART) project along Jalan Chan Sow Lin (Tunnel alignment), Kuala Lumpur. The study was divided into two parts, which was pre-tunnel and post-tunnel survey. In the pre-tunnel study, detail information of the subsurface was needed to avoid problems which can compromise safety. Due to constraint of the study area being traffic congested, limited spacing and time, not all data acquisition was done using RSPole-dipole protocol. Some of the survey lines were replaced by RSWenner 32SX (L and S) protocol. All the data were correlated with each other and with borehole data provided by the developer. The pre-tunnel survey results show the presence of many weak zones (fractures, voids, filled cavities and collapsed cavities) along the tunnel alignment and the depth of the rock

head was 1.25 – 10 meter. The post-tunnel survey was conducted in order to see and map the effect of grouting and tunnelling using the Tunnel Boring Machine (TBM). To assist the mapping of utilities and very shallow subsurface features the Ground Penetrating Radar (GPR) was used. The GPR result shows the presence of many utilities in the subsurface.

CHAPTER 1

INTRODUCTION

1.0 Engineering problems

In urban area, development is continuous. There are many development projects such as building of new offices, houses, shopping complexes, bridges, and roads. Development also involves repairing, upgrading and installing new utilities.

Development of urban area such as in the city centre will result in traffic congestion. To reduce this congestion, tunnels and flyovers are built. Such developments require proper and detailed planning, involving multi field specialists such as geophysicists, geologists, engineers and town planners. Collaboration among the relevant authorities is needed in order to get a better solution and coordination for the problems relating to development.

Traditionally, civil engineers depend on borehole data and soil tests for foundation design of building, road etc. However, the cost of each borehole is expensive. The boring work produces a vertically single point data. In order to map the whole area, combination and interpolation of various boring data need to be applied. To get a good and meaningful image of the subsurface, the number of boreholes needs to be increased, thus involved time and cost. Moreover, in urban area this will lead to traffic congestion and will cause inconvenience to people. The engineers also need information on utilities below the survey area in order to avoid boring and excavating problems. Hence, information of the subsurface before boring or excavation of the survey sites is indispensible to the engineers.

Methods which are nondestructive for initial survey are most welcome. Hence, geophysical methods which are nondestructive can be applied in the initial stage (screening). Most of the geophysical methods are based on survey line. The survey line can include drilling of one or two boreholes (instead of 3-4 boreholes). The geophysical data will be correlated with borehole data to produce an image of the subsurface. In addition, geophysical study can also be used to detect or to map underground utility by using electromagnetic waves.

Geophysical studies which provide nondestructive methods have recently been employed to reduce cost and numerous problems (Komatina and Timotijevic, 1999). Before starting any development, geophysical surveys are carried out to obtain as much initial information as possible about the condition of the ground and possible problems of the subsurface. The geophysical data can subsequently be used by geologists and engineers. These surveys have been used to provide information on many environmental and engineering applications such as groundwater table, slip planes, soil stratifications, etc.

Five common geophysical methods that can be applied to achieve the objective in mapping subsurface structures are gravity, magnetic, seismic, resistivity and Ground Penetrating Radar (GPR) which can save time and cost. Some of these geophysical methods pose fewer survey problems especially in urban area. Choosing a suitable geophysical method for the survey is very important. It depends on the objective, cost allocation and accessibility of site.

Each geophysical method has its strengths and weaknesses depending on the target and area of the survey. Geophysical methods such as gravity, magnetic, seismic, resistivity and ground penetrating radar (GPR) each have its limitations. For instance, the gravity method requires a sufficient density contrast between the target and host (surrounding medium). The magnetic method uses targets that contain magnetic materials. Both of these methods are not suitable to be used in urban area because of noise interferences produced by buildings and traffics. The seismic method is widely used in engineering surveys. This method identifies geological structures by measuring the physical properties (density) of materials in which sound waves travel. An energy source transmits an acoustic energy pulse into the ground sending sound waves downward. Depending upon the geological formations encountered, part of the energy is transmitted to deeper layers, while the remainder is reflected and refracted back to the surface. Sensitive receivers called geophones (land-based) or hydrophones (submerged in water) will receive and record the signals. The information is transmitted, amplified, filtered, digitized and recorded on magnetic tape for interpretation. However, since the receiver is very sensitive to noise, the seismic method is not an appropriate geophysical method to apply in urban area.

Resistivity and GPR methods have added advantages and also pose lesser problems for surveys in urban area compared to other geophysical methods. Time, penetration depth, space and traffic factors are the main issues that are always involved when the resistivity method is used in urban areas. To use the GPR method, getting a suitable time (when there is less traffic) is the only problem. This problem can affect the data quality. Hence, the resistivity and GPR methods are chosen since they are probably the most suitable geophysical methods that can be employed in an urban area. A study has to be made on resistivity acquisition techniques by introducing a new protocol in order to improve the data quality such as increasing depth of penetration and reducing noise. Precautions and planning must be done beforehand such as the site and the traffic flow survey. Traffic controllers are also needed at a busy area to control the traffic. In this thesis, both resistivity and GPR methods are employed to map the subsurface structures for the tunnel project.

1.1 Research objectives

The aim of this study is:

i. To develop new resistivity acquisition techniques (protocols) that can provide better image, deeper penetration and less noise.

ii. To determine a suitable geophysical method that can be used in an urban environment and any others.

iii. To test the effectiveness of the techniques in detecting and mapping underground features in urban area.

1.2 Problem statements

The main originality of this research work lies in the developing the 2-D resistivity data acquisition techniques (protocols) based on the arrays (Wenner, Wenner-Schlumberger and Pole-dipole) provided. The present acquisition techniques (protocols) have a few disadvantages such as penetration depth which was related to electrode spacing, resolution and high level of noise.

It is hoped that the new protocol will provide a better and higher resolution image with deeper penetration and low noise level. Moreover, the space limitation problem will be solved.

1.3 Layout of thesis

Generally, the content of this dissertation is organized as follows.

In Chapter 2, early studies using geophysical methods (seismic, resistivity, IP, GPR and TEM) applied to engineering and archaeological problems are discussed. However, only study on tunnelling using geophysical methods is highlighted.

Chapter 3 is devoted to the research methodology of 2-D resistivity method. The research involves developing new acquisition techniques by using three arrays (Wenner 32SX, Wenner-Schlumberger and Pole-dipole) to produced new protocols (RSWenner 32SX, RSWenner-Schlumberger and RSPole-dipole).

In Chapter 4, the general theory and principle of the geophysical methods (2-D resistivity and GPR) used in the survey are discussed.

In Chapter 5, the three models (Theoretical, Laboratory and Field model - miniature) were tested with new protocols (RSWenner 32SX, RSWenner-Schlumberger and RSPole-dipole). The field test was carried out with RSPole-dipole and RSWenner32SX protocols to see the suitability of the protocols selected.

In Chapter 6, the data acquisition at the study area (SMART TUNNEL, Kuala Lumpur) using RSPole-dipole and RSWenner 32SX protocols was discussed. GPR survey was used to detect utilities and shallow subsurface. The survey was divided into two parts, pre-tunnel and post-tunnel.

Chapter 7 discussed the results of the 2-D resistivity and GPR survey for pre-tunnel and post-tunnel along Jalan Chan Sow Lin, Kuala Lumpur.

Finally, in Chapter 8, conclusions on the 2-D resistivity study were discussed including recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Geophysical surveys are often used to provide accurate subsurface information while minimizing surface disturbance. This information is presented in ways that make sense to engineers and geologist, and provide feasible, cost-effective solutions to the project. Selection of the appropriate geophysical methods is based on project objectives and the site conditions. Seismic refraction survey is to provide compressional wave velocities to estimate rippability, depth of hard strata and bedrock. The surface wave survey is to provide subsurface shear wave velocity profiles for design and image weak zones in the subsurface. The 2-D/3-D resistivity imaging method is for karst and voids, the Self Potential (SP) and resistivity surveys are to map seepage paths (dams or reservoirs) while the resistivity and induced potential (IP) surveys are to delineate municipal waste landfills. The GPR surveys are to map steel reinforcing bars (rebar) in concrete, estimate asphalt and concrete thickness, and evaluate condition of concrete. The Electromagnetic induction (EM) and Ground Penetrating Radar (GPR) methods are to locate buried waste, pipes, and underground storage tanks, as well as for characterization of karsts.

2.1 Previous work

Before setting up the Tunnel Boring Machine (TBM), the subsurface information of the tunneling area and route ahead of tunnel alignment is very important to the engineers. Cavities or fault must be attended to as they will affect the TBM and cause a lot of problems and can compromise safety. Subsurface information will guide the engineers to problematic areas so that they can overcome problems by grouting cavities or divert the TBM if a dyke exists.

Brooke and Brown (1975) have outlined the applications of geophysical techniques to reduce engineering problems. Seismic refraction, gravimetry, and electrical prospecting are the survey methods that should be employed for locating concealed cavities. Several other geophysical methods such as seismic reflection or electromagnetic exploration may be suitable in very special cases where the geological configuration is an anomalous situation.

Petronio et al. (2007) utilized the tunnel-seismic-while-drilling (TSWD) method. The noise produced during mechanical excavation is used to obtain interpretable seismic data. This passive method uses accelerometers mounted on the advancing tunnel-boring machine (reference signals) together with seismic sensors located along and outside the tunnel. Data recorded by fixed sensors are cross correlated with the reference signal and sorted by offset. Similar to reverse vertical seismic profiling, cross correlated TSWD data are processed to extract the reflected wavefield. During the mechanical excavation of a 950-m tunnel through upper Triassic dolomite, a survey was performed to predict geologic interfaces. Faults intersecting the tunnel were observed on seismic TSWD data and later were confirmed by geostructural inspection. P-wave and S-wave interval velocities obtained by TSWD data along the bored tunnel were used to compute dynamic rock moduli to support tunnel completion.

Lorenzo and Flavio (2002) utilized the tunnel boring machine (TBM) extensively to mechanically excavate tunnels. To optimize the mechanical drilling and work safety, an estimate of the geology to be drilled is necessary. Using the elastic waves produced by the TBM cutting wheel, the seismic-while-drilling (SWD) information for predicting the geology ahead of the drilling front is obtained. This method uses accelerometers mounted on the TBM together with geophones located along and outside the tunnel, similar to the technique successfully used to drill oil and geothermal wells. Study of noise and the resolution of the signal produced by the large-diameter cutting head shows that non stationary noise separation can be achieved by locating sensors at the front and rear ends of the tunnel. The (higher) resolution in front of the TBM is limited by pilot delays, while the (lower) lateral resolution is limited by the radial dimension of the TBM. Analysis of seismic data acquired in a field test shows that P-wave and S-wave arrivals have a wide frequency band and high amplitude in seismic traces measured 700 m away from the drilling front. In comparison with SWD applications in wells, tunnel SWD technology has the advantage of allowing direct access to the tunnel front, which makes it easy to connect the TBM reference sensors for while-drilling monitoring. This method can be successfully applied without interfering with drilling activity to monitor tunnel excavation continuously, reduce risks, and optimize drilling.

Saxena (1996) had documented a case history that used geophysics to evaluate a project involving a DSC (Differing Site Condition) clause. Development of various water management areas in connection with construction of a 4-lane roadway in northeast Naples, Florida required blasting, excavation, and removal of shallow rock between the depths of 1.2 to 3.0 m (4.0 to 10.0 ft). The work commissioned was to conduct a three-stage investigation that consisted of:

i. Pre-Investigation Survey (PIS).
ii. Refraction Seismograph Velocity Profiling (RSVP) in a test section.
iii. Test borings/coring. Results of ultrasonic testing performed on rock cores indicated variability in seismic p-wave velocities determined by the field refraction seismograph versus laboratory ultrasonic testing.

Singh (1984) presented field results of shallow seismic reflections obtained with a propane-oxygen detonator (POD). The survey site was in a tin-mining area of the Kinta Valley in Malaysia. The shallow and irregular limestone bedrock is overlain by alluvial 'tailing' and virgin sediments. The survey was intended to delineate the topography of the bedrock, which is of vital importance in tin ore exploration and exploitation. Reflections at around 200 Hz were obtained from the shallow bedrock at about 25 m as well as from very shallow lithological interfaces. The interpretation of seismograms is supported by drill-hole lithological sections and synthetic seismograms. The data illustrate the successful use of shallow reflections for mapping irregular bedrock. Reflection seismics can provide better horizontal and vertical details than the refraction method.

Popenoe (1984) shows that the high-resolution seismic-reflection profiles mapped the shelf off northern Florida is underlain by solution deformed limestone of Oligocene, Eocene, Paleocene and late Cretaceous age. Dissolution and collapse features are widely scattered. They are expressed in three general forms;

i. Sinkholes that presently breach the sea floor, such as Red Snapper Sink and the Crescent Beach submarine spring.
ii. Sinkholes that have breached the seafloor in the past but are now filled with shelf sands.
iii. Dissolution collapse structures that originate deep within the section and have caused buckling and folding of overlying Eocene, Oligocene, and to a lesser extent, Neogene strata.

Although deformation caused by solution and collapse can be shown to be a continuous process, the major episode of karstification occurred in the late Oligocene and early Miocene when the shelf was exposed to subaerial conditions.

Cratchley et al. (1976) measurementing of the sound velocity (Vp) in the low-pressure tunnel of the Foyers hydroelectric scheme show that the values can be used as an index of rock quality in the granodiorite of the Foyers granite complex. Seismic refraction measurements at the surface have located a faulted and shattered zone of granodiorite approximately 50 m wide beneath superficial cover of silty sand and boulders. Resistivity measurements have given a similar indication. Both sets of measurements at the surface enabled two borehole sites to be pinpointed for detailed investigation of the fault zone by core logging, sonic logging and borehole to borehole sonic logging. This case history is an example of the effective use of geophysics at two levels which was to locate a zone of difficult tunneling ground from the surface and to survey the zone in detail with geophysical probes in two boreholes.

Ganerod et al. (2006) shows that results from site investigations, 2-D resistivity, refraction seismic and Very Low Frequency (VLF) on a section of tunnel near Trondheim. The 2-D resistivity data are most valuable for interpreting geological structures in the sub-surface. VLF can only identifies zones and does not indicate thickness, width or dip direction. In addition, this method is sensitive to technical installations. Refraction seismic is valuable for mapping depth to bedrock location and width of fracture zones but cannot indicate the depth or dip direction of such zones. With 2-D resistivity, the position of a zone is well identified. This method may also provide information on the depth and width of the zone as well as the dip direction. In most cases 2-D resistivity clearly identifies zones in the bedrock that can be observed as fault and/or fracture zones in the tunnel. The results described in this paper show a good correlation between the resistivity profiles, mapped structures on the surface and mapped zones in the tunnel.

Hyoung et al. (2006) described, in tunnel construction, information regarding rock mass quality and the distribution of weak zones is crucial for economical tunnel design as well as to ensure safety. Usually, the rock mass grade is estimated by observing recovered cores obtained by drilling or by physical parameters calculated in a laboratory using core samples. However, the high drilling cost limits the number of boreholes; furthermore, rough terrains can reduce the access of drilling machines to the survey sites. In such situations, surface geophysical methods such as electrical resistivity or controlled-source magnetotelluric (CSMT) can provide a rough estimate of the rock mass condition over the planned tunnel route. These methods can also map weak zones (faults, fractures, coal bearing zones, and cavities), which are characterized by a lower resistivity than the surrounding fresh rock mass.

Stanfors et al. (1985) discussed extensive geological and geophysical investigations for the Swedish Bolmen tunnel were performed in conjunction with the planning and design work, principally to locate zones of weakness in the rock that could significantly affect the line of the tunnel. The article discusses electrical methods for assessing the risk of water ingress, because of the very large effect water has on the electrical conductivity of rock. It is not only the quantity of water and amount of salt dissolved in the water that determine the electrical conductivity of the bedrock, but also the nature of the fissures and quantity of clay and weathering products in them. The resistivity measurement is made by measuring the voltage (V) (potential) between two inner electrodes (MN), and the current (I) for an electric current sent through the ground between two external electrodes (AB). The electrodes are placed at a depth of 200-300 mm along a line on the ground surface located symmetrically about the measuring point. Also discussed are correlations with electromagnetic measurements.

Nelson et al. (1982) presented three case studies investigating induced-polarization (IP) responses of a zeolite-bearing conglomerate and of two carbonaceous siltstones. The IP response of these noneconomic geologic materials can either mask or mimic the response from sulfide mineralization which is sought by electrical field surveys. The nonsulfide rock types which produce unusually high responses on IP field surveys were sampled by core drilling for chemical, mineralogical, and electrical laboratory study. The electrical response of core samples was measured in a four-electrode sample holder over the 0.03–1000 Hz range. Geologic description of the core, petrographic examination of thin sections, mineral identification by x-ray diffraction (XRD) and chemical analysis of samples supplemented the electrical measurements. A surface phase response of

20 mrad was obtained from field surveys over the Gila conglomerate at an Arizona location. Core samples of the Gila were examined in thin section and clast surfaces were found to be coated with a thin layer of zeolites. These zeolites project into pore spaces in the conglomerate and thus are in intimate contact with formation waters. A series of laboratory experiments suggests that zeolites cause most of the observed IP response. Phase responses as high as 100 mrad were measured with field surveys over siltstone and limestone sequences in western Nevada. Samples recovered from the Luning and Gabbs-Sunrise formations include siltstones containing small amounts of amorphous carbon. These siltstones are very conductive electrically and the high-phase response is attributed to polarization of the carbon-pore water interface. Low porosity in these carbonaceous siltstones enhances the phase response.

Zhou et al. (2002) studied sinkholes which are often a major hazard to development in areas underlain by carbonate rocks. Road and highway subsidence, building-foundation collapse, and dam leakage are a few of the problems associated with sinkholes. Structural instability associated with sinkholes can occur as a sudden collapse of the ground surface or as a less catastrophic, but recurring drainage problem.

The development of computer-controlled multi-electrode resistivity survey systems and the development of resistivity modeling software (Loke and Barker, 1995) have made electrical resistivity surveys more cost-effective and less labor-intensive than they were formerly. These surveys are commonly referred to as electrical resistivity tomography (ERT) or electrical imaging. The advancement of these techniques allows resistivity data to be collected and processed within a few hours and as a result ERT is becoming a more valuable tool in subsurface investigations (Zhou et al, 1999). A frequently occurring problem with ERT is the need to determine which of the many existing electrode configurations will respond best to the material changes in karst features. Each array has distinctive advantages and disadvantages in terms of depth of investigation, sensitivity to horizontal or vertical variations and signal strength. Setting aside the effects of ‘‘noise’’ (i.e., the effects of nearsurface local variations in resistivity which in themselves may place a limit on the detectability and resolution of karst features), application of an inappropriate array type often happen. Selection of an appropriate electrode array in resistivity surveying requires knowledge of the properties of the targets, the sensitivities of each array to a certain geologic feature and the budget of the project. The investigations presented in this paper show that the mixed array may be the most technically sound configuration but it significantly increases the amount of time and the cost to collect data. Among the three standard arrays (Wenner, Schlumberger and Dipole-dipole), the Dipole-dipole array provides the most precise delineation of potential sinkhole collapse areas and is the most sensitive to vertical boundaries. However, Dipole-dipole measurements are more likely to be affected by nearsurface variation noise. Under such circumstances, the Schlumberger array is a less effective alternative. These investigations indicated that the Wenner array could not provide a recognizable signature for a potential collapse area and should be avoided for sinkhole delineation.

Sergio and Giovanni (2006) studied the Hierapolis (Temple of Apollo), the principal deity of the city. While the foundations of this temple go back to late Hellenistic times, the present remains of the upper structure are from the 3rd century AD. Next to it is an underground chamber (called the Plutonion) from which poisonous gases emerge. This paper presents the results of a geophysical survey carried out to explore firstly the buried cavities or structures beneath the Temple of Apollo, knowledge of which is important to understand whether the Plutonion could be entered from the inside of the temple. Secondly to contribute to the ongoing evaluation of ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) as tools for research into subsurface archaeological features (voids, walls, etc.).

Two-dimensional ERT imaging was used to detect the presence of an active normal fault passing under the Temple of Apollo, as shown by geological, geomorphological and archaeoseismological observations. The resistivity profiles reveal the presence of conductive material (clay) covering the archaeological structures. The presence of active normal faults is indicated by the displacement of the bedrock and the conductive material on top of it. Man-made structures located under the Temple of Apollo were detected using three-dimensional GPR imaging. The results of the two survey methods applied were compared, assessing the relative merits and demerits of each technique. Their combined use was discussed in terms of providing enhanced views that are more informative than a single method.

The S-inversion method is to predict and forecast water-filled faults or fracture zones ahead of the front wall of a tunnel during tunnel excavation (Xue et al, 2007). S-inversion is an interpretation method of transient electromagnetic (TEM) data using the second derivative of the conductivity parameter based on the moving thin sheet approach. It is suggested for the technology of second derivative of vertical apparent conductivity, which was traditionally used in surface TEM data interpretation, the theoretical analyses and the method of numerical calculation. A real tunnel forecasting was studied for TEM surveys and results showed that the proposed method is effective and successful for exploring and predicting unfavorable geology during tunnel construction.

The electrotelluric geophysical method is an advanced exploration technique that utilizes a passive portable instrument (Villasenor and Davies, 1987). It is based on the analysis of the electric field present at the surface interface from which accurate information is obtained regarding lithologies and ore resources down to 40,000 feet beneath a surface point. Its applications range from early prospecting reconnaissance to subsurface studies in mining operations. Electrotelluric surveys conducted in coal fields of Central Utah illustrate the applicability and strategy used by the electrotelluric method in coal mine longwall development. These studies provided information regarding minor fault displacements and coal seams at depths of 1,500 to 1,700 feet below the surface.

A successful case history was applying the high-frequency passive source electromagnetic (EM) method and controlled-source audiomagnetotellurics (CSAMT) to investigate the Qiyueshan (Q) Tunnel route (Lanfang et al, 2006). The high-frequency EM system (EH-4, with frequency range from 12.8 Hz to 90 KHz) and the CSAMT system (V6-A Multipurpose Receiver with frequency range from 0.125 Hz to 8,192 Hz) were used for the data acquisition. The orthogonal components of the electromagnetic field were measured in the high frequency EM method, while scalar measurements of the electrical and magnetic field components were used in the CSAMT method. The relevant electrical properties of the earth were extracted from the electromagnetic profiles. High frequency EM has high resolution in the shallow earth but a smaller depth of exploration while the CSAMT method has a powerful signal but a lower resolution in the shallow earth. The integration of the two methods might be effective for the survey of the deep tunnel route. Q Tunnel, located in central south China has a length of 10 km and a depth of up to 900 m. Half of the tunnel goes through karst terrain where the geologic structures are very complex due to cavities, underground rivers and faults. The EM mapping results distinguished the electrical resistivity of different rock formations. Five low-resistivity areas and four high-resistivity areas were found and nine faults were verified by the EM method. These findings were very useful for the later engineering design.

A detailed gravity survey has been conducted over the Stour buried tunnel-valley between Sturmer and Long Melford in Essex (Barker and Harker, 1984). The resulting Bouguer anomaly map indicated that the density of the boulder clay filling the valley is higher than that of the underlying chalk. The interpretation of the Bouguer anomaly clearly indicated the subsurface position of the Stour buried tunnel-valley and calculations of the depth to the base of the valley fill have been attempted. Detailed resistivity sounding surveys at proposed borehole sites confirmed the gravity interpretation and provided more detailed information on drift lithology and thickness.

Integrated geophysical methods, including high-precision gravity survey, magnetism survey, high-density electricity survey, radioactivity radon gas survey, seismic method survey, ground temperature measuring, Hg measuring and nuclear resonance magnetism method have been applied to explore the underground palace of Emperor Qin Shi Huang Mausoleum. It is identified that the distribution area of the underground palace, the thinner tamped wall in the tamped burial mound, real sites of coffin chambers as well as grave pathway in the west direction through careful digging and integrated analysis and comparison should be most important discoveries in latest exploration for Emperor Qin Shi Huang Mausoleum (Liu et al, 2004).

Laboratory measurements of Radio Frequency (RF) complex permittivity had been made on a variety of "rocks" encountered in mining, tunnelling, and engineering works (John, 1975). An RF impedance bridge and a parallel-plate capacitance test cell were employed at frequencies of 1, 5, 25 and 100 MHz. The results predicted that low-loss propagation will be possible in certain granites, limestone, coals and dry concretes. Existing Very High Frequency (VHF) mining radar equipment should be capable of exploring into such rocks to distances of up to hundreds of feet. Useful but shorter probing distances are predicted for other coals, gypsums, oil shales, dry sandstones, high-grade tar sands and schists. Radar probing distances of less than 10 ft are predicted for most shales, clays and fine-grained soils. Uncombined moisture content is evidently the governing factor. Efforts were made throughout the experiments to preserve or simulate the original moisture content of the "rocks" in place.

Blasting near the access road to a new airport for the Town of St. Anthony, Newfoundland exposed a large open cavity (Maher et al, 1998). Although a site investigation had been previously carried out for the proposed airport development, its scope had been limited to investigation of overburden soils. Since the new airport was already partially completed, it became critical to locate any additional cavities before further construction took place. An integrated site investigation utilizing geological mapping, ground penetrating radar and gravity surveys in conjunction with core drilling was immediately undertaken. The airport is located on dolomitic limestone and evidence of karstic features is abundant. The geophysical surveys revealed that the rock was dissected by numerous open and/or clay infilled bedding planes. In the area of one of the proposed terminal buildings, the intersection of a thrust fault with a major NW-SE fracture zone was identified and was found to control the formation of small solution cavities. These particular ground conditions necessitated modifications to standard building foundation designs to ensure the integrity of the completed terminal building.

Rock-mass fracturing is a key parameter in rock-fall hazard assessment. However, traditional geologic observations can provide information only about discontinuities at the surface (Jeannin et al, 2006). In this case study, detailed ground-penetrating-radar (GPR) measurements (with antennas of 50 MHz, 100 MHz, 200 MHz, and 400 MHz) were conducted on a test site, using different acquisition configurations deployed on vertical cliff faces. Conventional 2D profile data, common-midpoint (CMP) survey data and transmission data were acquired to evaluate the potential use of radar waves to characterize the geometry and properties of the major discontinuities (fractures) within a Mesozoic limestone massif. Results showed that the continuity and geometry (orientation and dip) of the major observed fractures, which are crucial parameters for assessing rock stability, can be obtained by combining vertical and horizontal profiles measured along the cliff. Using 100-MHz antennae and reached a maximum penetration of 20 m, which limits the technique to rock volumes of a few tens of thousands of cubic meters. Significant differences in reflectivity along the detected fractures were observed, which suggests that the fractures characteristics vary in the rock mass. A radar velocity image was obtained using transmission data although the results were consistent with radar profiles on the cliff, they showed that the technique has little utility, beyond that of more traditional GPR methods, for delineating fractures in a rock mass.

Seismic reflection and refraction with different wave source were used to map the lithology interface and to detect the existence of some other features such as weak zone, fault, dyke, cavities etc. The results have to be compared with borehole log. This method needs a suitable and special wave source such as Tunnel Boring Machine. The resistivity method is used to identify the rock mass quality and weak zones in conjunction with the planning and design work. Monitoring the ground change will help engineers maintain the scope areas. Resistivity method was supported with some other geophysical or engineering method such as borehole, rock mass grade (estimated by observing recovered cores obtained by drilling) or by physical parameters calculated in a laboratory using core samples. GPR is one of the most reliable methods used to provide information about utilities and discontinuities at the subsurface. The information provided by this method is highly accurate but the limitations are resolution, depth of penetration (<10m) and noise.

Other geophysical methods (transient electromagnetic, IP, gravity and EM) were used in order to map and detect the lithology and weak zone. This method needs a very strong support data from engineering section (borehole etc.). From the previous work, electrical method (resistivity method) and GPR are the most suitable geophysical methods in void and cavity study. These methods are much more accurate, less noisy and requires less time and cost.

2.2 Conclusion

From previous works, the 2-D resistivity method is most suitable for interpreting geological structures in subsurface while seismic method is valuable for mapping depth of bedrock and fracture zones but cannot indicate the depth or dip direction of the zone but 2-D resistivity method can. The 2-D resistivity method used previously was the acquisition techniques with the standard of data level (n) and total number of data. Hence, the 2-D resistivity method was chosen in this research. This method has less noise effect, time and cost effective compared to some other geophysical methods. Noise from vehicles will affect the seismic data. As for the magnetic and gravity method, buildings, utilities and traffic would affect the reading. With a suitable array the 2-D resistivity method seems to be the most suitable method in urban areas for the detection of fractures, voids, filled cavities, collapsed cavities, pinnacles, cliff subsurface and overhangs that frequently occur in limestone area.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Introduction

The electrical resistivity method is one of the oldest geophysical methods, originally designed in the 1920s for mineralogic prospecting by the Schlumberger Company in France. Since then, the method has been improved for the engineering, environmental and archeology studies. There are a lot of arrays that can be used depending on the objective and site conditions. The most famous arrays are Wenner 32SX, Schlumberger and Dipole-dipole.

In this chapter, the different arrays are compared. This is to identify the suitability of the array towards the objective, site condition and time constraint since the study area is in an urban area where time and site condition are very limited.

3.1 The research

For development projects, information about the subsurface, to the depth of about 100 meter is needed. In addition to borehole information, geophysical and geological information would also help in guiding engineers and contractors in their decisions and planning. A large number of geotechnical problems arose during the construction of previous engineering projects located in the Kuala Lumpur Limestone Formation (Yeap et al. 1993; Bergado et al. 1987; Mitchell, 1985; Tan, 1986; Tan and Komoo, 1990). This project shows that it is important to have accurate geological subsurface information of a project site. There are a few studies on Karsts area which shows problems involved in such areas (Burger, 1992; Cavinato et al., 2006; Gue and Singh, 2000; Gue and Tan, 2001; Martin and Dietrich, 2005; Suleyman, 2003; Sedat and Nuri, 2003; http://www.jacobssf.com/articles/Genting%20Tunnel%20Design.pdf).

Limestone and cavities are closely related. The change of topography is drastic even at a very short distance. These phenomena will lead to fractures, sinkholes and other phenomena that can threaten human life (Giovanni, 2006). The karsts areas are very difficult for geophysics exploration (2-D and 3-D resistivity method) but with the existence of water, the resistivity method can be used efficiently (Sumanovac and Weisser, 2001). It is difficult to build a tunnel along the limestone areas. The tunnel boring machine (TBM) will pass through karst areas and encounter karstic system and groundwater which will cause problems during excavation (Suleyman, 2003). Many geophysical studies have to be conducted in karstic areas to avoid problems (Deceuster et al. 2006; Mac Donald et al. 2001; Jorge et al., 2005) and create methods of problem solving (Turkmen, 2003; Turkmen and Ozguzel, 2003).

Ground Penetrating Radar (GPR) is also used to study the response of the topsoil towards the GPR signal, its characteristic and data quality (Grandjean and Gourry, 1996). In this study, problems encountered while doing the survey and the solutions to overcome such problems will be discussed.

Geophysical methods are suitable tools for investigating this karsts region. The choice of geophysical method used depends on the target. Magnetic method can only be used to detect a magnetic target while gravity method, on the other hand, can only be used if there is a significant contrast in the density of the target relative to its surroundings. The seismic method uses sound wave, density and modulus elasticity. Seismic method requires source, receiver, acquisition design, noise, large area and a lot of capital. Among all geophysical methods available, the 2-D/ 3-D resistivity and GPR are the most suitable methods to be used in most situations. The resistivity method can be used to measure the conductivity of the ground to a certain limit with certain depth while the GPR method uses electromagnetic wave to see the reflection, refraction and diffraction of the shallow targeted object or subsurface.

This research uses two geophysical methods which are GPR and 2-D resistivity imaging. The GPR survey was to determine and map the utilities and shallow subsurface structures while the 2-D resistivity imaging was to detect and map the rock head, cavities and fractures. Since the target depth was less then 26 meter and with space constraint, a new acquisition technique using Wenner32SX, Wenner-Schlumberger and Pole-dipole arrays was proposed (RSWenner32SX, RSWenner-Schlumberger and RSPole-dipole).

The acquisition technique for the three arrays was developed and modified where the number of n level was increased to get maximum penetration depth, maximum data points and reduced noise (Appendix A). Table 3.1 shows the difference between the original and modified protocols of the Wenner, Wenner-Schlumberger and Pole-dipole array. Furthermore this study is to compare which protocol of the 2-D resistivity imaging method with the RSPole-dipole protocol can be used to fulfill the research objective compared to other protocols such as RSWenner32SX and RSWenner-Schlumberger in term of depth of investigation, sensitivity to horizontal and vertical variations and suitability towards the objective.