APPLICATION OF SURFACE WAVE AND GEOELECTRICAL RESISTIVITY METHODS IN GEOTECHNICAL SITE INVESTIGATION

KHAIZAL

UNIVERSITI SAINS MALAYSIA
2013

APPLICATION OF SURFACE WAVE AND GEOELECTRICAL RESISTIVITY METHODS IN GEOTECHNICAL SITE INVESTIGATION

by

KHAIZAL

Thesis submitted in fulfilment of the requirements for the degree of the Master of Science

July 2013

ACKNOWLEDGEMENTS

Alhamdulillah, All praise and adoration is due to Allah SWT, Lord of most compassionate and merciful.

I would like to offer my sincerest appreciation to main supervisor, Professor Dr. Mohd Nawawi Mohd Nordin of Universiti Sains Malaysia who suggested the use of surface waves analysis for this research. I am indebted to him for his useful suggestions, valuable time devotion and patience. I am also grateful for the opportunities given to me to join his research group for field work experience. I would also like to express my gratitude to co-supervisor Dr. Rosli Saad for his suggestions and support throughout the preparation of this thesis.

Also, my innumerable appreciation goes to Associate Professor Dr. Taksiah Majid for allowing me to use seismic refraction equipment. Furthermore, my heartiest thanks go to Dr. Adiat Nafiu Kola who inspite of his chain of engagements meticulously read this work and his contributions are acknowledged.

Special thanks go to Aceh Government and Syiah Kuala University in Aceh, Indonesia, for giving to pursue my educational advancements. Indeed it is a rare opportunity. This work would not have been a success if I did not enjoy the assistance and contributions of the following technical staff of the Geophysics laboratory section: Messrs Low Weng Leng, Mydin Jamal, Yaakop Othman, Shahil Ahmad Khosaini and Azmi Abdullah.

Equally important to be acknowledged are the geophysics postgraduate students: Messrs Ishola Saheed, Abdullahi Abdulrahman, Andy Anderson and Mogaji Anthony. I thank you all for the assistance received during this work. I am also thankful to Tan Chee Ghuan of School of Civil Engineering Universiti Sains Malaysia for his supports during the data acquisition campaign.

My appreciation also goes to my beloved parents: Jamaluddin Ridwan and Rohani for given me a good educational legacy and my siblings: Mustika Hadi, Yulizar and Rahmat Rizki for your supports, encouragement and understanding during my study.

Finally, I am indebted to my beloved wife Mira Intania and daughters: Afifah Bisyri and Atikah Farhana for their perseverance, spiritual supports and understanding throughout the duration of my studies. Without them, my graduate studies would not have been successful.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREATIONS

GRI	Geo-electrical Resistivity Imaging
MASW	Multichannel Analysis of Surface Wave
SASW	Spectral Analysis of Surface Wave
GPR	Ground Penetration Radar
P-wave	Compressional wave
S-wave	Shear wave
BH	Bore Hole
CPT	Cone Penetration Test
SPT	Standard Penetration Test
VST	Vane Shear Test
N-value	Standard penetration number
C	Current electrode
P	Potential electrode
V	Potential difference
I	Electrical current
1-D	One Dimensional
2-D	Two Dimensional
3-D	Three Dimensional
RES2DIVN	Resistivity Two Dimensional Inversion
RMS	Root Mean Square
SAS	Signal Averaging System
Ωm	Ohm meter
Hz	Hertz
SEG2	Society of Exploration Geophysicists 2
Km	Kilometer

GPS	Global Positioning System
CMP	Common midpoint
CMPCC	Common midpoint cross-correlation

PENGGUNAAN KAEDAH GELOMBANG PERMUKAAN DAN KERINTANGAN GEOELEKTRIK DALAM PENYIASATAN TAPAK GEOTEKNIK

ABSTRAK

Banyak kes kegagalan pembinaan telah dilaporkan dan kos bagi penyiasatan lapangan turut meningkat disebabkan oleh ketiadaan maklumat subpermukaan. Kelakuan fizikal dan mekanikal bagi bahan-bahan geologi biasanya tidak dapat dijangkakan. Kebelakangan ini kaedah konvensional iaitu penggerudian, ujian penusukan kon (CPT), ujian bilah ricih, ujian penusukan piawai (SPT) telah lama digunakan dalam penyiasatan tapak geoteknik untuk tujuan kejuruteraan awam. Namun, pelaksanaan bagi kaedah-kaedah ini memerlukan kos yang tinggi berbanding jumlah kos pembinaan projek. Kebiasaannya hanya tiga ke lima lubang-gerudi digunakan oleh jurutera geoteknik bagi aplikasi kaedah ekstrapolasi lubang-gerudi untuk meliputi keseluruhan kawasan lapangan. Teknologi termaju geofizik mampu menyelesaikan masalah tersebut. Kaedah-kaedah ini relatifnya lebih menjimatkan kos, cepat, tidak memusnahkan dan lebih teguh data yang diperolehi. Keadah-kaedah geofizik bagi gelombang permukaan dan pengimejaan kerintangan geoelektrik telah dijalankan di tiga tapak penyiasatan: Merbok Kedah, Balik Pulau and Nibong Tebal Pulau Pinang di Semenanjung Malaysia. Kaedah “continuous fixed roll along” telah digunakan bagi pengambilan data pengimejaan gelombang permukaan. Susunatur Wenner-Schlumberger telah dipilih bagi pengimejaan keberintangan geoelektrik. Keputusan-keputusan bagi ketiga-tiga tapak kajian menunjukkan bahawa di Merbok, kaedah geofizik berjaya mengesan tanah baki di atas batuan dasar, berjaya mengesan pengendapan marin di atas batuan dasar terluluhawa di tapak kajian Balik Pulau dan juga keputusan munasabah iaitu mengesan zon halaju rendah di tapak kajian Nibong Tebal. Dua lubang-gerudi termasuk ujian SPT telah dijalankan di setiap tapak kajian. Perbandingan bagi nilai gelombang ricih dan keberintangan geoelektrik dengan data lubang-gerudi menunjukkan bahawa terdapat persetujuan baik dan ketara antara mereka. Walaupun kaedah geofizik menunjukkan keputusan yang baik, data lubang-gerudi dalam kuantiti minimum adalah turut perlu dalam penyiasatan tapak kajian geoteknik. Hasil kajian ini menunjukkan bahawa penggunaan kaedah-kaedah geofizik dapat memberikan maklumat geoteknik dan membantu mengurangkan kos penyiasatan lapangan.

APPLICATION OF SURFACE WAVE AND GEOELECTRICAL RESISTIVITY METHODS IN GEOTECHNICAL SITE INVESTIGATION

ABSTRACT

Many cases of constructions failure have been reported and the prohibitive cost of investigation has also increased due to the unavailability of subsurface information. The physical and mechanical behaviours of geological materials are commonly unpredictable. Lately conventional methods that include: drilling, cone penetration test (CPT), vane shear test, standard penetration test (SPT) have long been directly used in geotechnical site investigation for civil engineering purpose. Yet, in its implementation these methods required more cost compared to the total cost of construction project. Commonly three to five boreholes only, which geotechnical engineers using extrapolate method of boreholes to cover entirely site area. Advanced geophysical technologies are capable of solving these problems. These methods are relative more cost-effective, fast, non invasive and more robust of data acquired. Geophysical methods of surface wave and geo-electrical resistivity imaging methods were carried out at three investigation sites: Merbok Kedah, Balik Pulau and Nibong Tebal Pulau Pinang in Peninsular Malaysia. Continuous fixed roll along method was implemented for two dimensional surface wave field data acquisition. A Wenner-Schlumberger array was selected for geo-electrical resistivity imaging. The results of the study at the three sites showed that for Merbok site, the geophysical methods have successfully delineated residual soil over bedrocks and successfully detected marine sediments over weathered granitic bedrocks at Balik Pulau site as well as also reasonable results of detected low velocity zone at Nibong Tebal site. Drilling of two boreholes which include SPT test were conducted in each of the sites. Comparisons of shear wave velocity and geo-electrical resistivity-value with boreholes data showed good agreement and consistence. Although, geophysical methods showed good results, borehole data even in minimum quantities are still needed in the geotechnical engineering site investigation. The results of the study show that the application of surface wave and geo-electrical resistivity methods can be complement of conventional methods and in turn reduce the cost of site investigation.

CHAPTER 1

INTRODUCTION

1.0 Research motivation

Each civil engineering structure is constructed above and within subsurface (soils and rocks). Soils and rocks are materials that occurred naturally; hence they have heterogeneous behaviours, complex physical and mechanical properties. Geological factors influence designs, constructions, and engineering structures such as buildings, bridges, roads, dams, tunnels, mines, and landfills. Uncertainties in the planning and designing play an importance role in engineering structures failures (Bremmer, 1999). Therefore, it is necessary to investigate the natural existing conditions of subsurface before the construction of engineering structures.

In the past, a variety of conventional geotechnical investigation techniques that have successfully developed and used to investigate subsurface conditions include cone penetration tests (CPT), standard penetration tests (SPT), drilling, sampling and laboratory test. The use of these methods for subsurface investigation is often limited from three to five points of investigation only. This is because the cost required for such investigation is relatively expensive. On the other hand, the purposes of designing and maintaining structures required subsurface geotechnical information to cover the entirety of the study area. It is necessary to ensure that structures produced truly meet the appropriate technical requirements in terms of safety and reliability. Coduto (2001) explained that in order to get subsurface information that is really reliable, a minimum of one borehole is required for an area which is between 200 to 400 m^2. However, for residual soil layers one borehole per 200 to 400 m^2 is not appropriate (Coduto, 2001). Lack of availability of comprehensive subsurface information has led to many cases of construction failures. Conventional investigation methods of investigation are destructive, invasive, time consuming and highly technical. Furthermore, these methods are not effective and not environmental friendly.

Laboratory testing of result exposed to quality samples which highly difficult to obtain truly undisturbed samples if cohesionless soils. There is a proposed solution to good quality cohesionless undisturbed samples by freezing method, yet it requires the cost, and if many samples necessarily require treatment with the particular expertise. In the liquefaction case, cohesionless soils paramount importance analysed to determine dynamic behaviour (shear modulus, Gmax). So far, parameter Gmax based on undisturbed sample testing in the laboratory is typically using a cyclic triaxial test, resonant column test (Khan et al., 2008; 2010) and bender element test (Zhou et al., 2005).

Geophysical survey techniques offer environmental sustainable strategies and solutions to various problems and challenges of geotechnical engineering site investigation. Geophysical survey techniques applied to geotechnical site investigation method is non-invasive and non-destructive. They provide the best approach for characterization of soil deposits in geotechnical engineering purpose. Applications of engineering geophysics method improve the spatial data resolution by providing either two dimensional (2-D) or three dimensional (3-D) subsurface image of the study area and in turn reduce the volume of borehole. Geophysical survey methods are fast, cost effective and can be easily implemented along linear sections to obtain a two dimensional profile of near surface layers (Soupios et al., 2007; 2008).

For several decades, many geophysical methods have been available and successfully applied to reconnaissance near surface anomalies of earth. Ground penetration radar (GPR), geo-electrical resistivity imaging (GRI) and surface wave methods are among the near surface geophysical methods. Recent research has shown that integration of a number of geophysical and geotechnical data to assess the condition of an embankment in relation to fill materials and track geometry was demonstrated by Gunn et al. (2008). Geo-electrical resistivity model imaging methods can be successfully applied to the investigation of characterising and monitoring earth embankments (Chambers et al., 2007). Geo-electrical resistivity and electromagnetic methods are powerful tools in environmental and geotechnical site investigations (Pellirin, 2002).

In Pulau Pinang Peninsular Malaysia, Rosli et al. (2003) has been successfully using seismic refraction method and 2-D geo-electrical resistivity imaging for mapping of depth, buried boulders location and bedrocks surface. Zuriati et al. (2009) conducted a study in the coastal reclamation area at Tanjung Tokong, Pulau Pinang using 2-D geo-electrical resistivity imaging and has successfully detected buried boulders and salt water intrusion. Azwin (2011) also has used 2-D geo-electrical resistivity imaging and seismic refraction method for geotechnical engineering problem at several locations in Peninsular Malaysia.

In the landslide investigation, geophysical survey methods (ground penetration radar and geo-electrical resistivity imaging) have been successfully applied by Friedel et al. (2006), Sass et al. (2008). Le Roux et al. (2011) have used

2-D geo-electrical resistivity imaging and seismic compressional wave tomography for determination thickness parameter and volume in the deep seated landslide. However, surface wave methods are still rarely used. Recently, surface wave method has become method of particular interest in the subsurface geotechnical engineering site investigation. Karray et al. (2009; 2010) have used modal analysis of surface wave method in geotechnical site investigation. Using surface wave method in the geotechnical characterization of a river dyke was analysed by Karl et al. (2011) and Raptakis (2012). They have used surface wave and compressional wave methods for assessment of pre-loading effect on dynamic soil properties and efficiency in geotechnical aspects. Also Zhou et al. (2009) have evaluated ground improvement for liquefiable deposits using shear wave velocity measurement.

Seismic shear wave velocity has good engineering properties. This is because seismic wave velocity propagation is related to mechanical behaviour or engineering properties of materials. On the other hand, geo-electrical resistivity is the physical properties only. Mechanical properties are related to shear strength parameters and this can be used to calculate the bearing capacity of subsurface geo-materials. Dynamic stiffness of the materials, expressed as dynamic Young's modulus and dynamic shear modulus are directly related to seismic wave velocities. These are important mechanical properties of soil layers. General correlation for local geology case between shear wave velocity and standard penetration test (N-SPT) has been reported by Thaker and Rao (2011), Brandenberg et al. (2010), Maheswari et al. (2010) and Dikmen (2009). Correlation between standard penetration test (N-SPT) to small strain dynamic shear wave modulus (Gmax) has been demonstrated by Anbazhagan and Sitharam (2010) and Anbazhagan et al. (2012). The dynamic shear wave modulus (Gmax) increasing importance for the liquefaction verification analysis of the earthquake safety of earth (Cao et al., 2011 and Trupti et al., 2012).

1.1 Research objectives

The objectives of the study are to:

i. Investigate the efficiency of surface wave and geo-electrical resistivity methods for subsurface geotechnical engineering site investigation.
ii. Infer the subsurface stratigraphy of the study area from results of interpretation of geophysical data.
iii. Validate the geophysical results with borehole log and standard penetration tests data and determine engineering parameters or properties of the subsurface materials in the study area.

1.2 Scope of study

In this study, mainly the surface wave method has been used. The 2-D geo-electrical resistivity model imaging also used as additional data in order to get more detailed results of the subsurface geology. Moreover, these two geophysical methods correlated and validated with conventional boreholes lithology and standard penetration test (SPT) data.

Three study areas were identified which are Merbok in Kedah, Balik Pulau and Nibong Tebal in Pulau Pinang. The processing of surface wave data was conducted using seisImager software package from Oyo Corporation. The 2-D geo-electrical resistivity survey with modified Wenner-Schlumberger array was conducted in the study area. This modified array is sensitivity to both horizontal and vertical variations compare to some other arrays (Loke, 2001). The 2-D geo-electrical resistivity imaging data was processed using RES2DINV software from GEOTOMO Pulau Pinang, Malaysia.

1.3 Rational of study

Surface wave and geo-electrical resistivity methods in environmental and engineering studies are given an exigent attention among geophysicists. They are considered powerful and mature tools in near surface geology and geotechnical site investigations. For the latter, improvements in surface wave and geo-electrical resistivity data analysis are considered an indispensable research tool for near surface geo-environmental and geo-engineering site characterizations. The surface wave and geo-electrical resistivity surveys are not only efficacious used in onshore but also in offshore areas.

In the United State and European countries, surface wave and geo-electrical resistivity technologies have been applied to near surface geophysics exploration. However, in the Southeast Asia (Indonesia), according to the author knowledge is a new tool and little research has only been done using these methods for geotechnical site investigations. This research is part of a campaign to make surface wave and geo-electrical resistivity methods as one of the tools in geotechnical site investigations in Indonesia. However, the fundamental principles, concepts and advance knowledge of acquisition, processing and interpretation data are very necessary.

1.4 Thesis arrangement

Generally, the outline of this thesis is organised as follows:

In Chapter 2, historical of surface wave development, theory and principles of methods used in this study, which is surface wave method, 2-D geo-electrical resistivity inverse model are briefly explained and discussed.

Chapter 3, the materials and methods of this study are explained. This chapter included about data acquisition, data processing and inversion. The equipments, principles of acquisitions, field procedure test and data processing are conversed in this chapter.

Chapter 4 explained results of Merbok Kedah, Balik Pulau and Nibong Tebal Pulau Pinang. These chapters included explanation about data surface wave method and geo-electrical resistivity model image interpretations. There are also correlations with the conventional boreholes record for the interpretation of results. In this chapter 4, the results of surface wave method and 2-D geo-electrical resistivity inversion model survey for geotechnical site investigation problem are discussed. The discussions are about different geological setting of three sites, processing issues of surface wave method and correlation shear-wave velocity parameter with N-value SPT data.

Finally in Chapter 5, the conclusions of the surface wave method in geotechnical site engineering investigation were discussed. Some recommendations of future work are also suggested in this chapter.

CHAPTER 2

SURFACE WAVE AND RESISTIVITY THEORY

2.0 An overviews of surface wave method

Generally, seismic waves involved two types: body waves and surface waves. The variation of a force on a body produces stresses and strains that propagate within the medium as waves called as body waves. The waves exist depending on the material properties and on the geometry of the body and a propagation velocity depending on the elastic modulus of the medium. The wave propagation within the medium body is compressional P-wave and shear wave (Figure 2.1) (Strobbia, 2002).

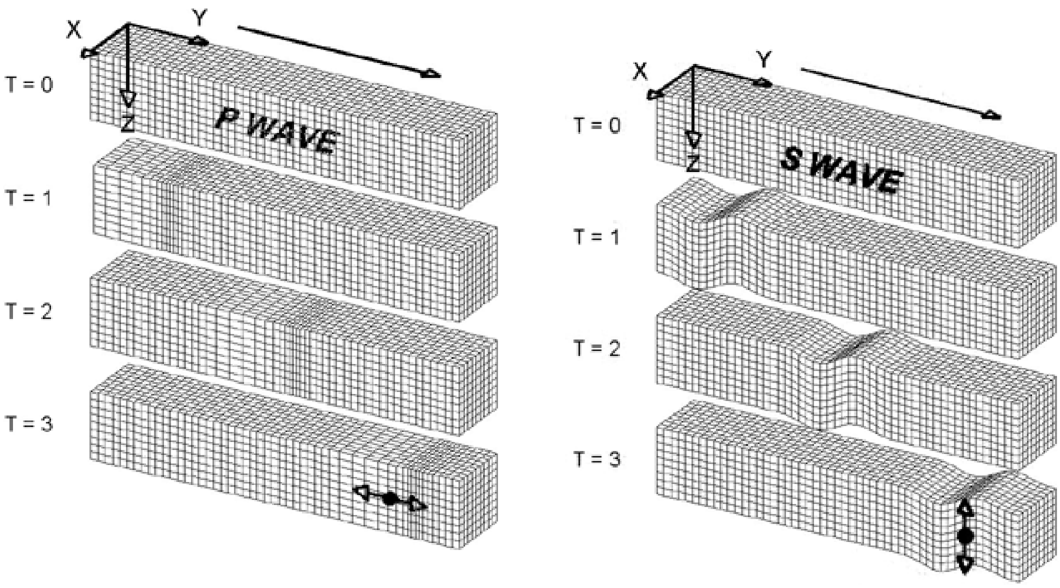

Figure 2.1: Body waves, P wave and S wave propagate inside the medium (After Strobbia, 2002).

The compressional wave called P-waves that the travel motion parallel to the direction of waves propagation. A particle motion perpendicular to the direction of waves propagation are shear waves or called also S-waves. When waves propagation within medium is bounded by a free surface, that a phenomena occurs are waves propagation generated near the surface or surface waves (Pei, 2007).

The surface wave method in its development has experienced ups and downs. They are called surface waves because amplitude decreases exponentially with increasing depth and propagating parallel to the earth's surface without spreading energy through the earth's interior. Surface wave can be Rayleigh wave or Love wave (Strobbia, 2002). Figure 2.2 show surface wave properties propagation.

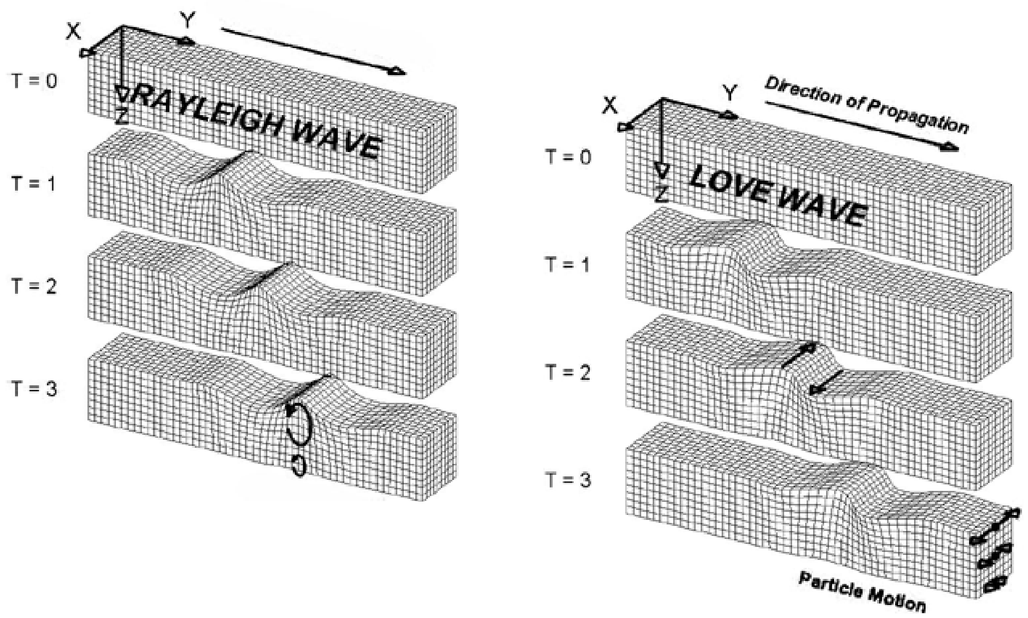

Figure 2.2: Surface waves, Rayleigh wave and Love wave, propagate parallel to the body surface without spreading energy towards the interior (After Strobbia, 2002).

Rayleigh waves travel such that the wave motion is parallel to the direction of wave propagation with particle motion in a retrograde elliptical motion. The Rayleigh waves result from the interaction between compressional P-waves and vertically polarized shear-waves. Conversely, Love waves travel such that the wave motion is perpendicular to the direction of wave propagation, consisting of horizontally polarized shear-waves. In the homogeneous medium, Rayleigh wave velocity propagation less than the shear wave velocity.

The propagation of surface waves in a vertically heterogeneous medium (variations of the elastic properties with depth) shows a dispersive behaviour. Dispersion means that different frequencies have different phase velocities; in particular, the geometric dispersion, in opposition to the intrinsic dispersion due to the material, depends on the geometry of the tested subsoil.

In a homogeneous medium, the different wavelengths sample different depths of the subsoil, but being the same material, all the wavelengths have the same velocity (Figure 2.3A). If the medium is not vertically homogeneous, for instance if it is layered, with layers having different mechanical properties, the different wavelengths sample different depths to which different mechanical properties are associated. Each wavelength propagates at a phase velocity depending on the mechanical properties of the layers involved in the propagation (Figure 2.3B).

In 1930s, early study pertaining to shallow seismic surface wave methods to civil engineering applications was developed at Gottingen University, Germany. At these times, capability of electronic computer device was less adequate, processing of dispersive wave and inversion for stratified media was still difficult. The first paper on near surface wave methods was published by Jones (1958). The method was based on in-situ measurement of the dynamic properties of soil by vibration methods. The glorious finding pertaining to the surface wave methods in civil engineering application appeared in the early 1980s. Stokoe and Nazaruddin (1983) and Nazaruddin (1984) have introduced spectral analysis of surface wave (SASW) to the investigation of subsurface and pavements.

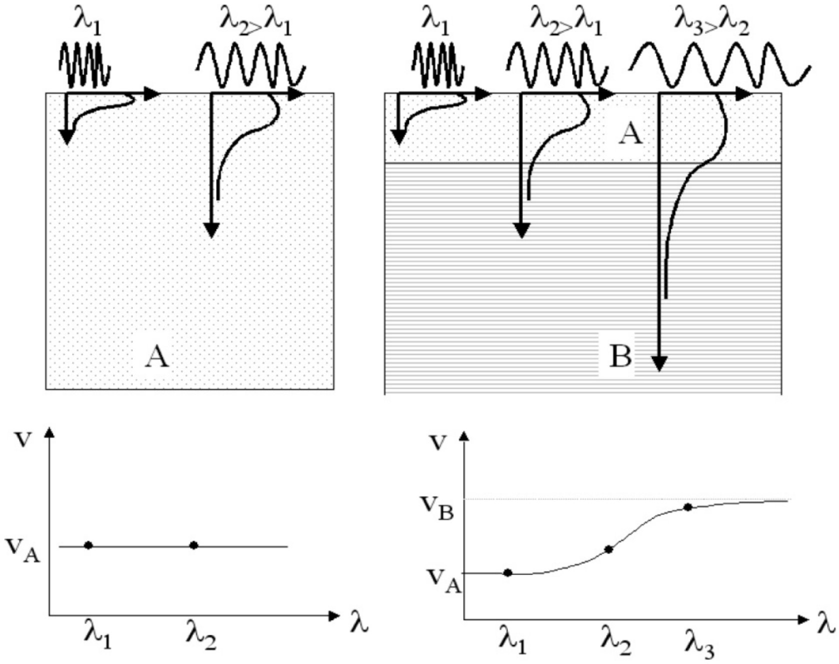

Figure 2.3: In a homogeneous half space (left) all the wave lengths sample the same material and the phase velocity is constant. When the properties changes with depth (right) the phase velocity depends on the wavelength, forming dispersion curve (After Pei, 2007).

The SASW method uses two pairs of low frequency geophones are planted to soils surface. For signal recording, an impulse source (sledgehammer and drop weight) as a source energy generated. The recorded time-domain history for increasing receiver spacing and source to first receiver distances converted to a Fourier transform. Dispersion curve can be constructed from the measuring difference phase Rayleigh wave velocity at distance between the two receivers as a function of frequency. The inversion of the dispersion curve to computed velocity curve performed using fundamental mode only. The derived shear-wave velocity considered as one-dimensional profile (shear-wave velocity to depth) underneath the midpoint of two receivers spacing.

Basic concept of SASW, the phase difference spectrum can be converted to a time difference (as a function of frequency) using equation 2.1-2.3. As these mathematical operations are carried out at for a variety of frequencies, an extensive dispersion curve is generated.

$$\Delta t(f) = \frac{\phi(f)}{2\pi f} \tag{2.1}$$

where

$\Delta t(f)$ = frequency-dependent time difference,

$\phi(f)$ = cross-spectral phase at frequency f,

f = frequency to which the time difference applies.

If the two time functions analyzed are the seismic signals recorded at two geophones a distance d apart, then the velocity, as a function of frequency, is given by:

$$V(f) = \frac{d}{t(f)} \tag{2.2}$$

where

d = distance between geophones,

$t(f)$ = term determined from the cross-spectral phase.

If the wavelength (λ) is required, it is given by:

$$\lambda(f) = \frac{V(f)}{f} \tag{2.3}$$

Latter in 1990s and early 2000s, surface wave method has grown more advances. Tokimatsu (1997) studied development of seismic methods using active surface waves. Park (1999) successfully developed surface wave methods called multi-channel analysis surface wave (MASW) and inspired researchers about the development of multi-channel analysis of surface wave. In a surface wave testing in Vancouver, Canada, comparing between MASW calculated Vs and borehole measured Vs (Xia et al., 2002) where average differences is less than 15 %. In MASW method, a linear array of 12 (or more) common vertical geophones with natural frequency of 4.5-14 Hz is used for recording the surface vibrations generated by impulsive or vibratory sources.

The MASW data processing, a dispersion image is constructed using Fourier transforming the time-space $(t - x)$ domain into a frequency-phase velocity domain. The dispersion image allows the identification of dispersion trends from the pattern of energy accumulation and the extraction of dispersion curve from the ridge picking (Pelekis and Athanasopoulos, 2011). Hayashi (2012) explained that in these complex velocity models, an observed dispersion curve can be considered as a series of phase velocities whose amplitude is the maximum at each frequency. Presently, three types of multi-channel surface wave computational dispersive processing methods have been used; these are as follows:

i. Frequency-wave number spectrum $(f - k)$, as reported by Yilmaz (1987), $(f - k)$ domain frequently used in 2-D data processing. Time-space $(t - x)$ is transformed into the $(f - k)$ domain from phase velocity identification through the relation: $V = \frac{f}{k}$, with V phase velocity addressed to the frequency f and wavenumber k.

ii. McMechan and Yedlin, (1981) have introduced 2-D dispersion image which time-space $(t - x)$ data transformed by slowness-frequency $(Tau - p)$ domain.

iii. Phase-shift transform as analyzed by Moro et al. (2003) is a method of transformation with the most robust and accurate phase velocities than others. Phase-shift transform is a composite scheme of $(f-k)$ and $(Tau - p)$ domain methods.

In surface wave method, the most important theory is the calculation of phase-velocity for layered velocity models. Park et al. (1998) has briefly described theory of transformation used to dispersion image:

$$U(x,w) = \int u(x,t)e^{iwt}dt \tag{2.4}$$

$U(x,w)$ expressed as:

$$U(x,w) = P(x,w) \cdot A(x,w) \tag{2.5}$$

with $P(x,w)$ and $A(x,w)$ are phase velocity and amplitude spectrum, respectively. Equation 2.4 can be derived as follows;

$$U(x,w) = e^{-i\phi x} \cdot A(x,w) \tag{2.6}$$

with $\phi = \frac{w}{c_w}$, w = frequency in radian, and c_w= phase velocity for frequency w.

Figure 2.4 show the transformation time-space $(t - x)$ domain processing to dispersion curve or relation between phase velocity and frequency. The MASW method, data inversion is usually based on the fundamental mode of wave propagation, although higher mode can generate surface wave velocity profile more accurate.

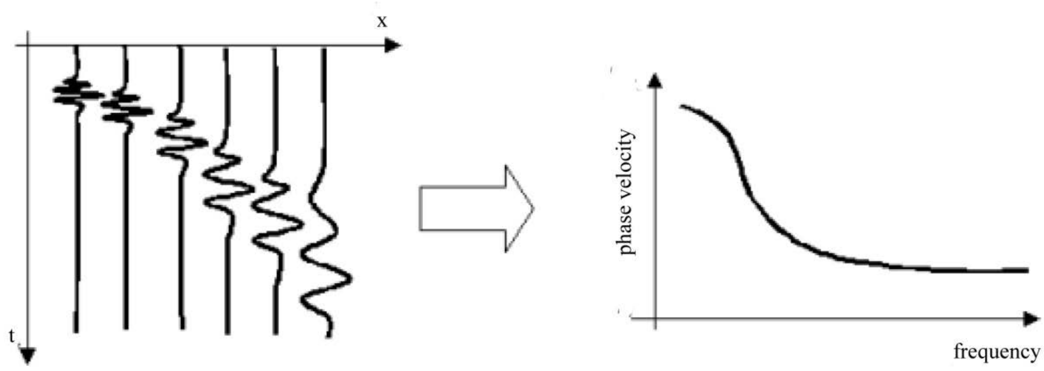

Figure 2.4: The forward model processing of acquired seismic data can estimate the experimental dispersion curve at a site (Modified after Strobbia, 2002).

2.1 Inversion of surface wave dispersion data

The surface wave inversion process is the act of inferring elastic properties such as density, shear wave velocity profile, and thickness from dispersion curves created (Xia, 1999). Three steps in utilization the surface Rayleigh wave dispersion properties are; field data acquisition, reconstruction of dispersion curve and inversion of a dispersion curve. Reconstruction of dispersion curve has been explained in the previous subsection. In order to determine shear-wave velocity profile (shear wave velocity versus depth) that properly identified Rayleigh wave, dispersion curve is prerequisite. In the steps of surface Rayleigh wave dispersive properties, inversion of dispersion curve is probably the most difficult and key factor to obtain a reliable near-surface shear-wave velocity profile (Cercato, 2011). The problem cannot be solve directly (unique solution) and requires an optimization technique to find the most probable solutions.

Formula for determining the dispersion curve corresponding to soil profile defined by a number of homogeneous layer and the thickness, shear and longitudinal velocity and soil density for each layer. The effect of poison's ratio ranging from 0.2-0.49 on Rayleigh wave velocity at a particular depth has been found to be significant by Karray and Lefebre (2010) and thus suggests a careful consideration of all available information before assuming the value of poison's ratio to be used in the analysis.

The inversion process of forward model dispersion curve start with initial model of shear wave velocity followed by the calculation of the corresponding dispersion curve. The difference between the experimental and theoretical curve (objective function) is determined as misfit or RMS (root median square). If greater than expected, value is revised and an updated so as to generate reliable shear-wave velocity. Minimise objective function calculated by a number of iterations. Automatically iterations (inversion) conducted through the employed algorithms with local and global search.

Researchers have developed local search algorithm: least-square method with Levenberg-Marquadt algorithm (Xia et al., 1999), least-square method with smoothness constraints (Song et al., 2007), least-square approach with inequality constraints (Cercato, 2009). Limitation local algorithm is inversion strategies that are proned to being trapped by local minima. This problem can be avoided by global search algorithm such as genetic algorithms, simulating annealing artificial neural network, wavelet transform, Monte Carlo, pattern search and particle swarm optimization. In the surface Rayleigh wave velocity dispersion, global search algorithms are advance methods of dispersion curve inversion. The surface wave data processing, author has calculated using software local search algorithm technique.

The typical dispersion curve (phase velocity versus frequency) for fundamental mode, 1st higher mode, 2nd higher mode, and 3rd higher mode is shown in Figure 2.5. The higher mode surface waves propagate faster than the fundamental mode.

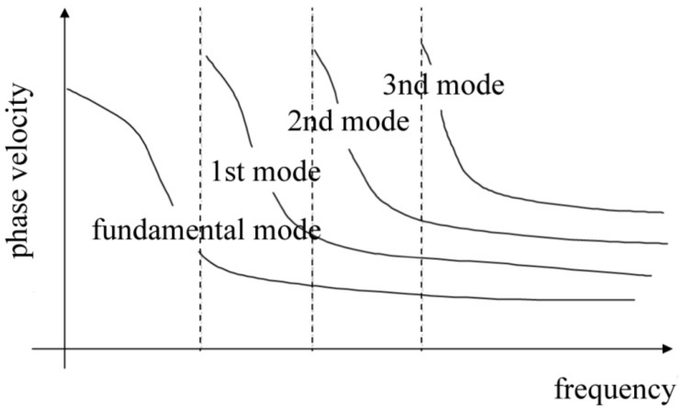

Figure 2.5: Dispersion curves of higher-mode surface waves. For the same frequency, higher modes exist only above their cut-off frequency and propagate faster than the fundamental mode (Modified after Strobbia, 2002).

In the vertically heterogeneous media in subsurface, the Rayleigh wave propagation is actually a multi-modal phenomenon for stratigraphy, at each same frequency given difference wavelength and difference shear-wave velocity. Higher mode can be penetrated deeper than fundamental mode (Figure 2.6). Figure 2.7 demonstrates dispersion curve within three types: normal, inverse, and irregular. A normal dispersion curve results from a profile where shear-wave velocity increases with depth. For a profile where shear-wave velocity decreases with depth, a reverse dispersion curve will be observed over some range of frequency. For an irregular shear-wave velocity profile, phase velocities show a complex relation with frequencies. The respectively of dispersion curve type results difference the shear-wave velocity curves.

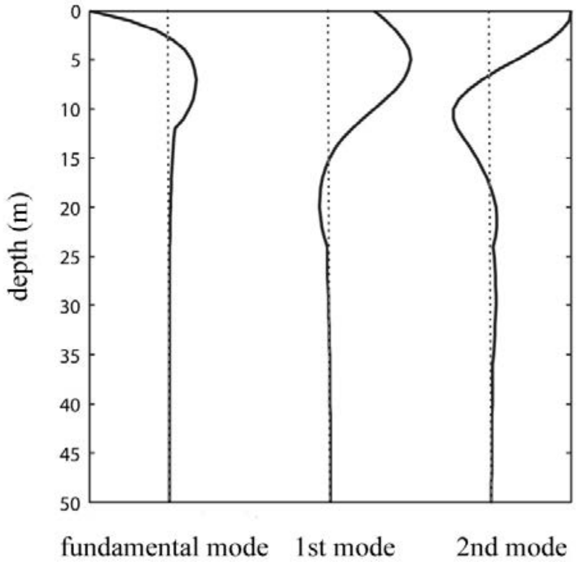

Figure 2.6: Difference modes, at each same frequency given difference velocity and difference wavelength. Higher modes penetrate deeper than fundamental mode (Modified after Pei, 2007).

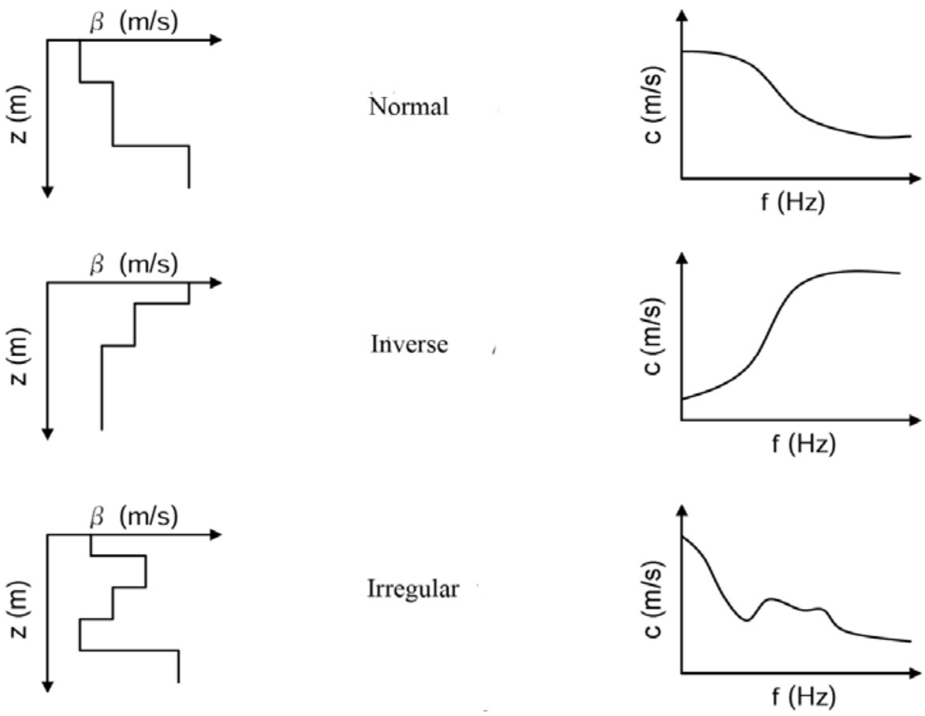

Figure 2.7: Three types dispersion curve (phase velocities versus frequencies): normal, inverse and irregular (Modified after Pei, 2007).

2.2 Geo-electrical resistivity method (basic principles)

Geo-electrical resistivity method was first developed in the early 1900s. Surface geo-electrical resistivity test for mineral and groundwater exploration has been commonly used from 1970s. It is now successfully used to monitor ground water contamination, landslide monitoring, and subsurface cavities and fissures locating. Electrical resistivity principle is measurement of material behaviour to retard the flow of electrical current or resistance to movement of charge (Awang et al., 2009). Figure 2.8 shows the electrical resistivity measurement as used when an electrical current (I) is passed into the ground through two electrodes and the voltage or potential difference (V) is measured across a second pair of electrodes (Reynolds, 1997).

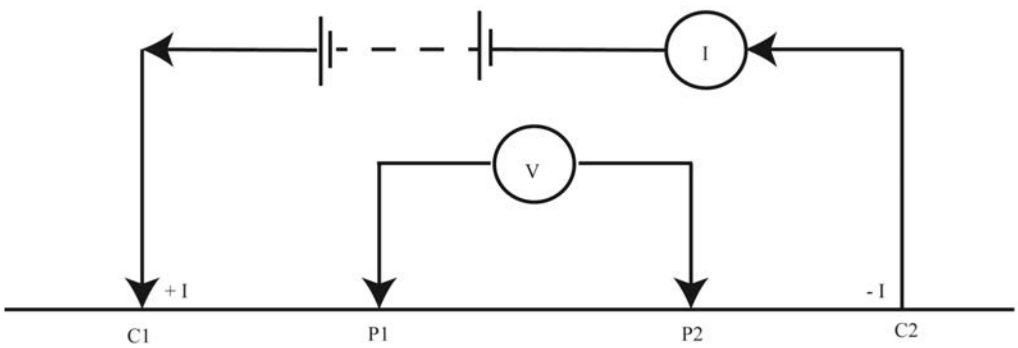

Figure 2.8: Electrode configurations in resistivity where (P_1 and P_2) are the potential electrodes and (C_1 and C_2) are current electrodes (Modified after Reynolds, 1997).

Geo-electrical resistance measurement according to Ohm's Law equation is shown in Equation 2.7.

$$R = \frac{V}{I} \tag{2.7}$$

with R is electrical resistance (Ω), V is potential (volts) and I is current (amps). The resistivity ρ (Ωm) for simple body is defined as follows:

$$\rho = R\frac{s}{l} \tag{2.8}$$

with R is electrical resistance (Ωm), s is cross-sectional area (m^2), l is length of cylinder media (m) when multiply with factor distance between the four electrodes; it can be gives the parameter apparent resistivity (ρ_a) as shown in equation as follows:

$$\rho_a = k \cdot \rho \tag{2.9}$$

where k is the factor of electrode distance geometric.

Loke, (2001) has explained that the calculated geo-electrical resistivity value is not the true resistivity of the subsurface, but an apparent value that is the electrical resistivity of a homogeneous ground that will give the same resistance value for the same electrode arrangement. The relationship between the apparent electrical resistivity and the true electrical resistivity is a complex. To determine the true subsurface electrical resistivity from the apparent electrical resistivity values is the inversion problem (Loke and Baker, 1996). Electrical resistivity properties can vary with direction called anisotropy.

In the geological materials, direct current flow by electrolytic conduction. Occurs by relatively slow migration of ions in a fluid electrolyte and controlled by pore fluid. Pore geometry mineral grains of matrix contribute little, except if metal ore geological materials show high variation in electrical resistivities. Table 2.1 showed geo-materials variations of nominal electrical resistivity.

Table 2.1: Nominal resistivity value for geo-materials (Loke, 2001)

Materials	Nominal resistivity (Ωm)
Granite (weathered)	$3x10^2$-10^6
Sandstones	1-7.4x10^6
Limestones	5x10-10^6
Clays	1-10^2
Alluvium and sand	10-8x10^2
Clay (very dry)	50-150
Gravel (dry)	1400
Gravel (saturated)	100
Quaternary/recent sands	50-100
Lateritic soil	120-750
Dry sandy soil	80-1050
Sand clay/clayey sand	30-215
Sand and gravel	30-225
Consolidated shales	20-2x10^3
Soil (40% clay)	8
Soil (20% clay)	33
Schists (calcareous)	20-10^4

2.3 Two dimensional geo-electrical resistivity imaging

For two dimensional (2-D) geo-electrical resistivity imaging survey, the Wenner-Schlumberger array (Figure 2.9) was used in this study. The Wenner-Schlumberger protocol array is hybrid method, used because this array more resolution to vertical and horizontal changes in subsurface with overlapping data levels. Dipole-Dipole array gives good resolution to horizontal changes.

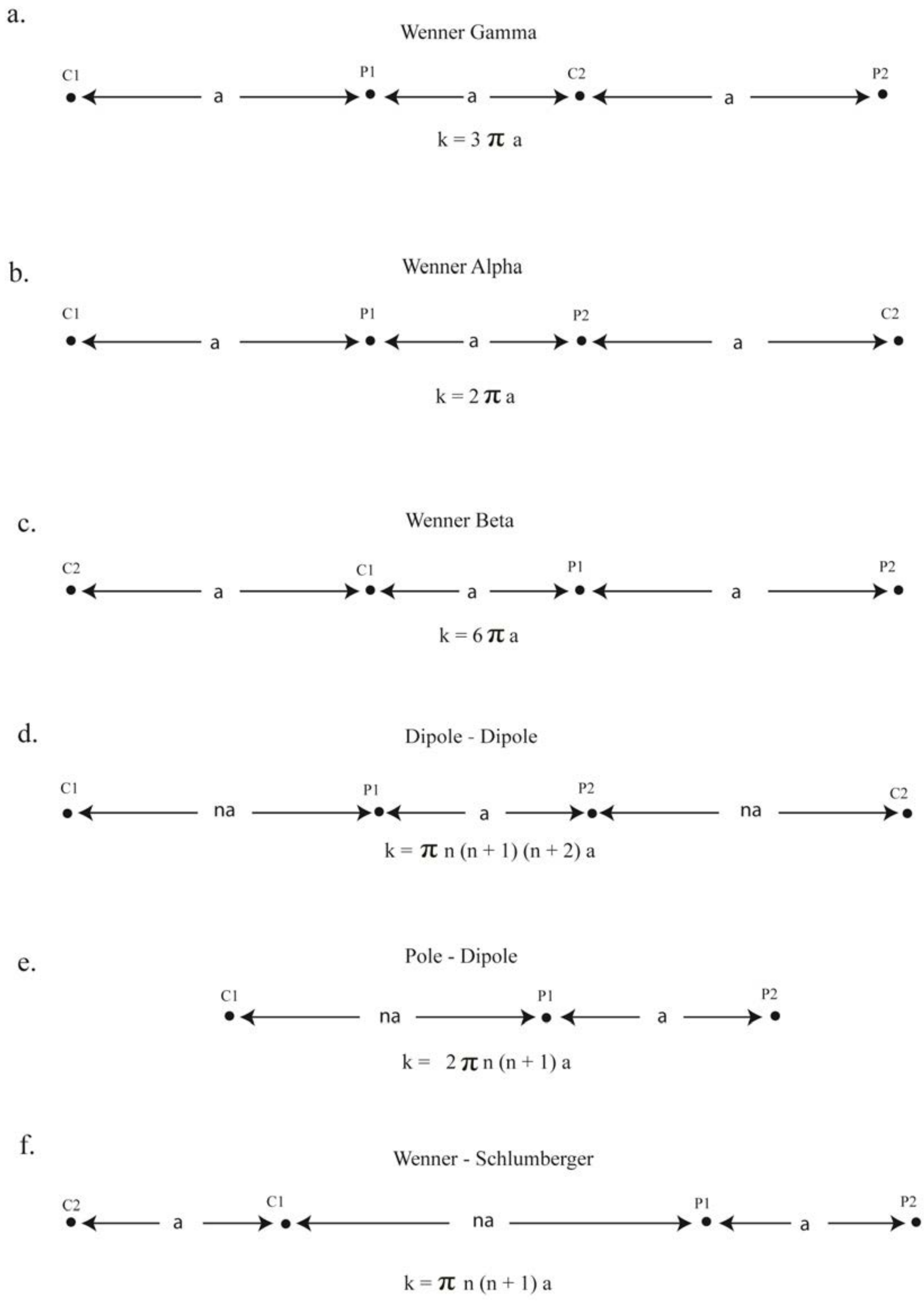

Figure 2.9: Common protocol array used in geo-electrical resistivity model surveys with geometric factor k. Wenner-Schlumberger array and Dipole-Dipole array have two parameters a and n, where a is length, n is the separation factor (After Loke, 2001).

Forty one electrodes were connected to a multi-core cable with constant spacing and straight line. The sequence of measurements to build up pseudosection showed in Figure 2.9. The selection active electrodes for each measurement using a computer controlled system. With constant spacing a long survey line, a series of measurements are made to give a complete horizontal and vertical coverage of the subsurface of the investigation area.

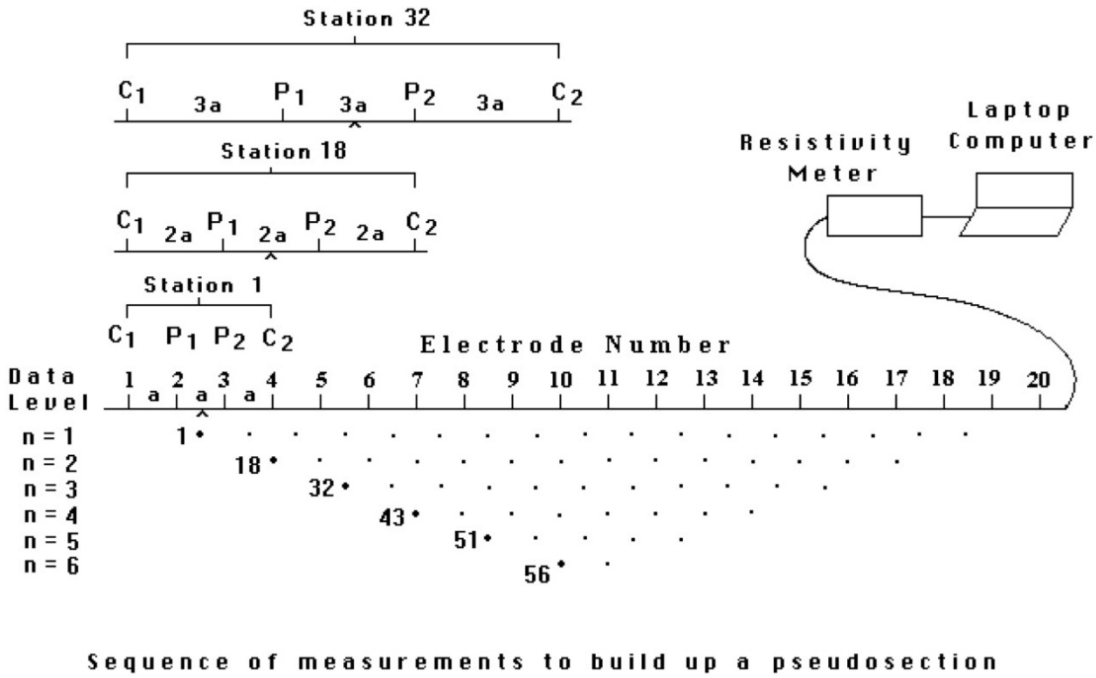

Figure 2.10: Electrode configuration two-dimensional geo-electrical resistivity model survey and the sequence of measurements used (After Loke, 2001).

The data processing is carried out using inversion programme (RES2DINV.EXE) developed by Loke and Baker (1996). This program uses implementation of the smoothness constrained least-square method based on the Gauss-Newton optimization technique. The geo-electrical resistivity of two-dimensional model, apparent resistivity values match with the measured apparent resistivity values from the field survey. The misfit or root mean square (RMS) error