Chapter 2
Theoritical Consideration

2.1 Introduction

It is essential to mention a basic phenomenon of the resistivity method. Due to the theory of induced polarization pertains to much of the resistivity principle. Theoritically, a given response is related to the electrochemical activity within the ground that contains mineral grain and pore-filling solution. Both resistivity and induced polarization methods look into this phenomenon but differ in scale of activity. The principles of resistivity and induced polarization will only be concerned with the surface contact resistivity method.

2.2 Resistivity method

2.2.1 Theory

The surface contact electrical method uses an artificial current generated from a generator or batteries. This current is driven into the ground and effects on, or within, the ground. Earth responses are obtained by measurements of differences of potential, ratios of potential differences, or some parameter that is related directly to these variables. The fundamental theory involved in each of the different methods is the same and is predicated upon the validity of Laplace's equation for obtaining the electrical potential and the pattern of current flow about one or more current electrodes placed on, or within, the ground (*Keller and Frischknecht*, 1979).

The resistivity principle invokes Ohm's law, which expresses electrical properties of matter under an electric field. This method, based on the direct current definition, assumes the earth to be *uniform*, *homogenous* and *isotropic*. If an artificial current is generated with a variable frequency, the response from the subsurface involves the complex resistivity principle. This will described in section 2.2.2.

The potential, or potential gradients measured depends on the region far away from current electrodes. In practical field surveys, electrical prospecting is used to observe the apparent resistivity that is derived from the measured potential gradient, or the potential itself, and the driving current under the given electrode configuration. In actuallity, the earth is a *heterogeneous*, *anisotropic* body and, therefore, the assumption is invalid and the term "*apparent*" is used to represent the measured resistivity. *Van Nostrand and Cook* (1967) suggested that apparent resistivity usually falls within range of true resistivity of the materials within the ground over which measurement are made. And so far the apparent resistivity sometimes rises above or falls below the true resistivity of all of the materials present (*Van Nostrand and Cook*, 1967).

In considering the basic principle of earth resistivity, *Keller and Frischknecht* (1979) stated that the theoretical basis of resistivity was based on two assumptions: *Ohm's law* and the *divergence condition.* Laplace's equation is obtained by combining these assumption.

In practical field survey, a four-point electrodes array which composes of two current electrode and two measuring potential electrodes is generally used. Set up parameter of the array is illustrated in Figure 2.1. The symbols M and N are the current electrodes with current strength +I and -I, same magnitude but opposite sign, whereas A and B are the measuring potential electrodes. The formula used to calculate resistivity is generalized as:

$$V=\frac{\rho I}{2\pi}\left[\frac{1}{R_{AM}}-\frac{1}{R_{MB}}-\frac{1}{R_{AN}}+\frac{1}{R_{NB}}\right] \quad\text{.......................................(2.1)}$$

where the resistivity defined as;

$$\rho=\frac{2\pi V}{I}K \quad\text{...(2.2)}$$

hence,

ρ = resistivity of measured material

I = impressed current from constant current source

V = measuring voltage

K = geometrical factor of the array

2.2.2 Resistivity of earth materials

There are many kinds of earth materials which can affect the electrical prospecting. A wide range of electrical conductivity occurs in earth material depends on whether the material is a pure substance or a mixture of several substances. The resistivity of these material depends upon the electrical conduction of their texture. Most metallic minerals can conduct an electrical current easily. Most other minerals have very little ability to conduct an electric current. Such minerals are insulating materials and include most of the rock-forming minerals. *Kearey and Brooks* (1991) stated that certain minerals, such as native metals and

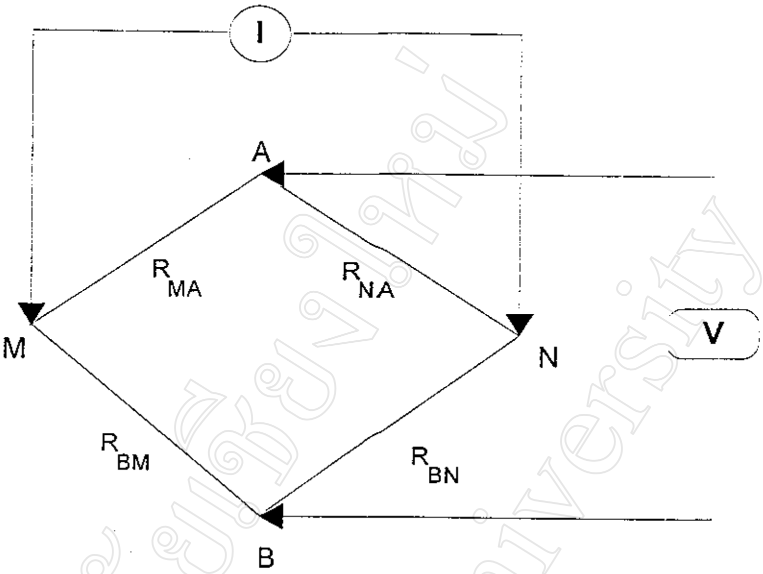


Figure 2.1 Four point electrode and set up parameter.

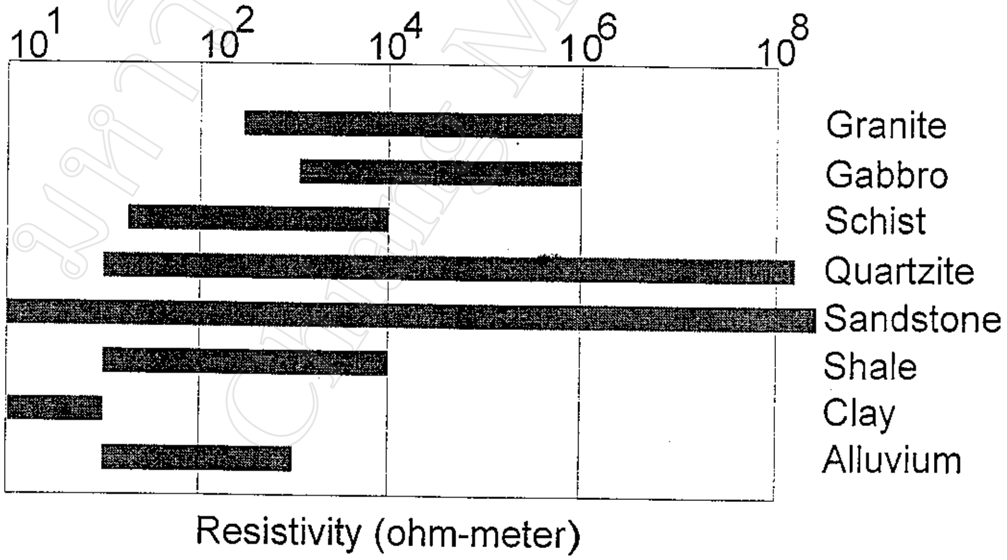


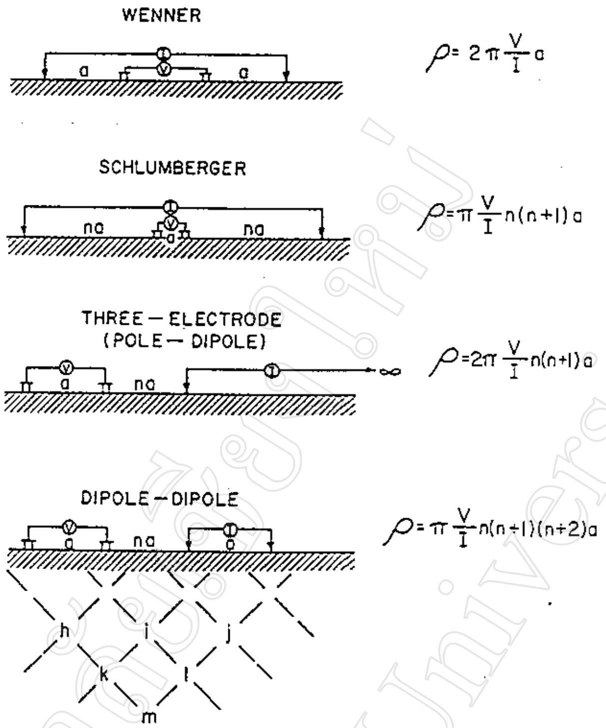
Figure 2.2 Range of resistivity variation in some rock (after Kearey and Brooks, 1991).

graphite, conduct electricity via the passage of electrons. Most rock-forming minerals are, however insulators, and electrical current is carried through a rock mainly by the passage of ions in pore water. Thus most rocks conduct electricity by electrolytic rather than electronic processes (*Kearey and Brooks*, 1991).

Several metals, such as gold, copper, platinum, and silver, occur in native form and conduct electricity by virtue of their high electron mobility. However, gold, copper, platinum, and silver are hardly common rock-forming minerals, even in the deposits where they occur (*Sumner*, 1976). The resistivity of earth material varies widely and depends on many factors, such as porosity, grain size, and the resistivity of connate water. Figure 2.2 shows the variation of resistivity of some common rock.

2.2.3 Array configurations

On the basis of potential distribution, the zone of measurement can be separated into three zones. Array configuration can be classified from these measuring zones. The first zone is located inner between current electrodes, C1 and C2. Array configurations concerned with this zone are the Wenner and Schlumberger arrays. The second zone is located around one of the current electrodes, C1 or C2. The array used to measure this potential distribution around current electrode is the pole-dipole array. The third zone is located far away from the current dipole. The array used for this field is the dipole-dipole array. Setup parameters used in these arrays are shown in Figure 2.3 (after *Sumner*, 1976 and *Techawan*, 1995).



(after Sumner, 1976)

Figure 2.3 Arrays set up and their resistivity formula.

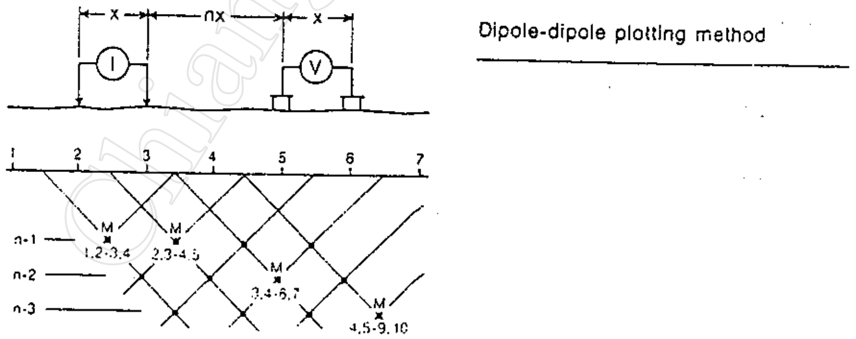


Figure 2.4 Pseudosection plot of sounding and profiling.

All geophysical methods of prospecting need to know the depth that the survey can investigate. *Beck* (1982) stated the depth of investigation is that depth which contributes most to the total signal measured on the ground surface. Under identical experimental conditions the Wenner and Schlumberger arrays have depths of investigation of 0.35b and 0.125b respectively, where b is the current electrode separation. For dipole-dipole and pole-dipole arrays, the depths of investigation are of 0.26b and 0.18b, respectively. On the basis of resolving power, Wenner array is the best, defined as 100% which better than the Schlumberger array about 10%. The Dipole-dipole and pole-dipole arrays have resolving power only 70% and 50%, respectively, of that of the Wenner array (*Beck*, 1982). Depths of investigation are summarized from *Bertin and Loeb* (1976), *Roy and Apparao* (1971), *Bhattacharya and Sen* (1981), *Beck* (1982), and *Techawan* (1995).

Resistivity prospecting is suitable for observing an anomalous zone that has lower resistivity values than the surrounding. Both lateral and vertical changes of resistivity can be located. The survey is designed realizes in its objective regardless of the nature of the target, the target location, or the target's environment. There are three methods of resistivity prospecting, each designed for a specific purpose.

The vertical electric sounding method of surveying is suitable for locating subsurface body that has somewhat different resistivities in its upper and lower layered earth model. It is commonly used for ground water investigations. The array configurations usually used for this method are the Wenner and Schlumberger arrays. These arrays give a higher resolution of vertical changes and have a greater depth of investigation than other arrays (*Seigel*, 1967).

The resistivity profiling technique is designed for investigating lateral changes in resistivity. The target is usually a vertical dike-liked structure. Array configurations popularly used are the pole-dipole and the dipole-dipole. The dipole-dipole array provides high resolution of lateral resistivity changes but its disadvantages are that a large crews is needed and it requires higher power source. While the pole-dipole array is the best array in this work but its response does not have a symmetrical shape (*Sumner*, 1976).

Though the vertical electric sounding and resistivity profiling techniques are appropriate for the different kinds of work but they can be combined to optimize survey cost and operating time by expanding the arrays into multiple potential electrodes. Figure 2.4 illustrates an array setup that is commonly used nowadays. The potential differences can be measured by several pairs of electrode during the operation. Potential electrodes can be expanded serially as required by the survey target. Though increased distance between current and potential electrodes increases depth of investigation, a large increase in current is necessary to increase the signal level above the noise level.

2.3 Induced polarization method

2.3.1 Theory

The theoretical consideration is simply demonstrated in time domain by how an R-C, resistor-capacitor, circuit behaves in an electric field, as shows in Figure 2.5(a). The ground acts as simple capacitor that is driven by a direct electric current with an appropriate time duration due to ensure that the current flows steadily. After that the current is abruptly cut off and the result is shown that the voltage does not drop to zero but, instead, drops to some value, *the overvoltage*, and then dies down with time, as shows in Figure 2.5(b). This phenomenon is not similar to an R-C circuit which in its decay response starts from a maximum magnitude and decay over time exponentially. Therefore, a subsurface mechanism seems not easily represented by a simple R-C circuit but must be represented by a more complex electrical circuit. *Keller and Frishknecht* (1979) stated that the peculiar form of the decay voltage actually observed in rocks indicates that a simple R-C circuit is inadequate to explain the behavior of current flow at a very low frequency.

In actually, the induced polarization effect come from two major causes, electrode polarization and membrane polarization.

Electrode polarization is the effect that occurs when a mineral grain is in contact with a pore-filling solution. The interaction between the pore-filling solution and the mineral grain can be represented by the internal pore path, with and without obstruction, of the metallic mineral grain. This is illustrated in Figure 2.6(a). The electrical circuit used to

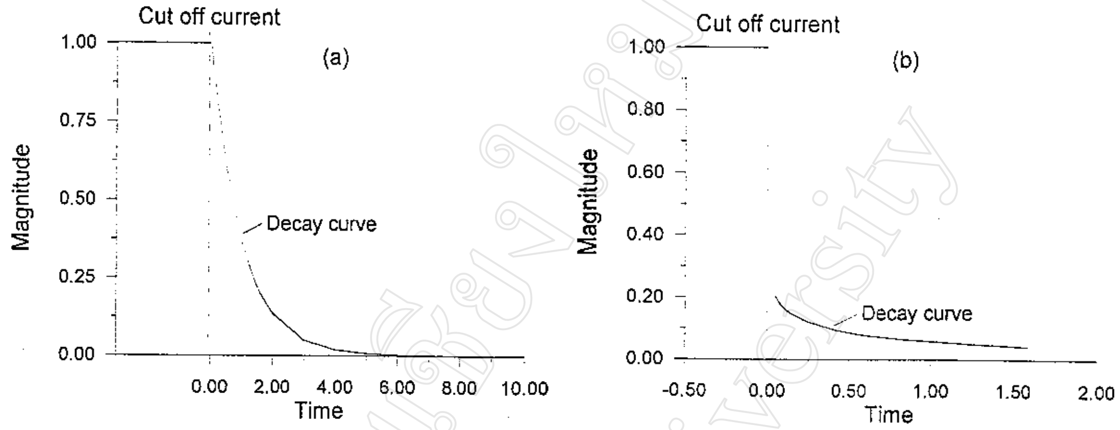


Figure 2.5 Decay characteristic of (a) R-C circuit and (b) induced polarization (modified after Keller and Frischknecht, 1966).

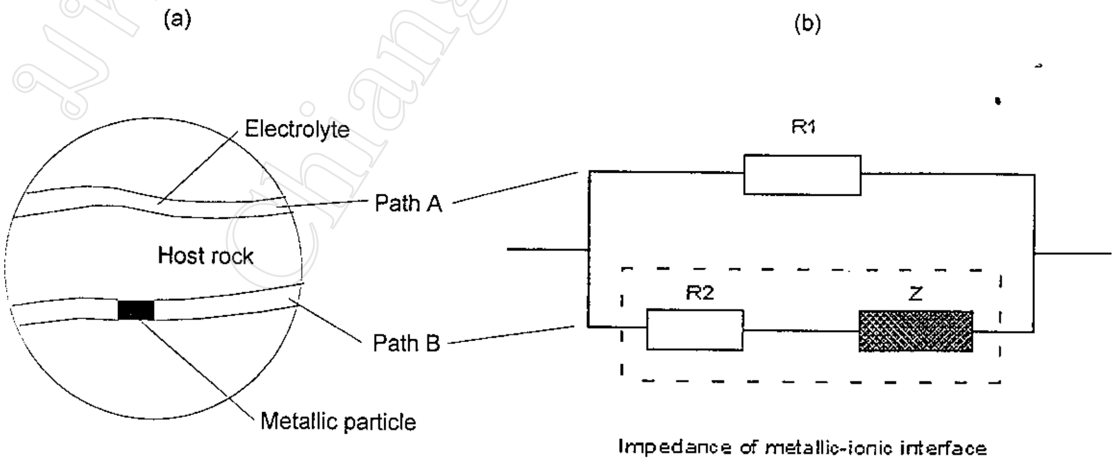


Figure 2.6 Illustration represents (a) rock pore passage with and without metallic mineral and (b) its R-C electrical circuit.

demonstrate is shown by an R-C circuit in Figure 2.6(b) (after *Keller and Frischknecht*, 1979). Whereas many authors, including *Sumner* (1976), *Pelton et al.* (1978), *Major and Silic* (1981), *Jordan* (1990), and *Johnson* (1990) have used the practical model based on an expression of *Cole and Cole* (1941) to represent this model.

While an external electric field is applied across the metallic-ionic interface, there is an accumulation of positive and negatice charges at both side of the interface. This action is shown in Figure 2.7 and called electrode polarization effect.

The qualitative expression of many factors causing an electrode polarization effect was summarized by *Keller and Frischknecht* (1979). There are mineral content (Figure 2.8), mineral grain size(Figure 2.9), porosity in rock(Figure 2.10), current density (Figure 2.11), frequency of current source (Figure 2.12), and percent of fluid-filled in pore space (Figure 2.13).

Second, the membrane polarization occurs from the charge accumulation at some point in pore passages that there are an excess negative charge on clay particles, cleavage faces, or edges of layered and fibrous minerals. This causes the accumulation of a diffuse cloud of positive charges in pore passages. This cloud will affect on the ability of negative charge to move along the pore passages. This phenomenon is illustrated in Figure 2.14(a). If an external force is applied to these pore passages, the positive and negative charges move apart to each side of the pore passages as shown in Figure 2.14(b), this activity will made the selective membrane cause in the polarization effect, namely *membrane*

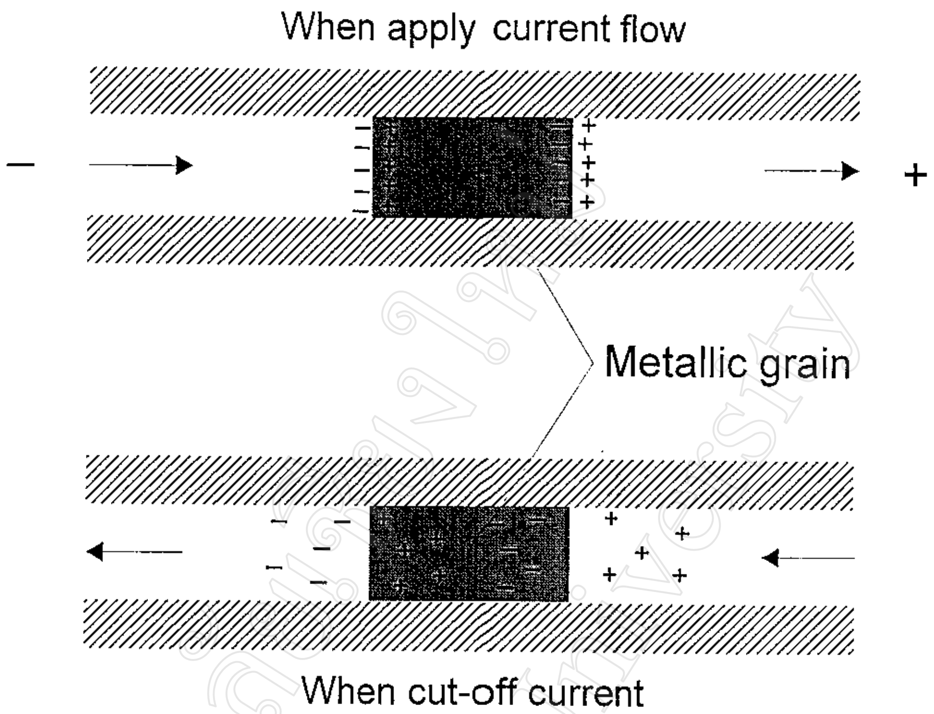


Figure 2.7 Electrode polarization effect due to metallic grain in rock.

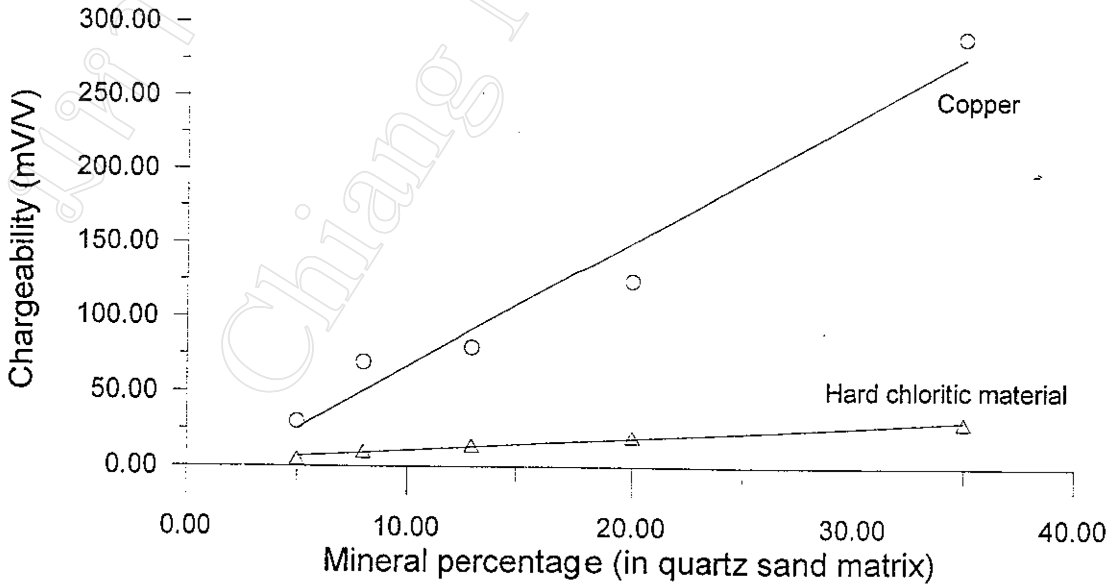


Figure 2.8 Relationship of polarization effect with mineral content (modified after Bacon, 1965).

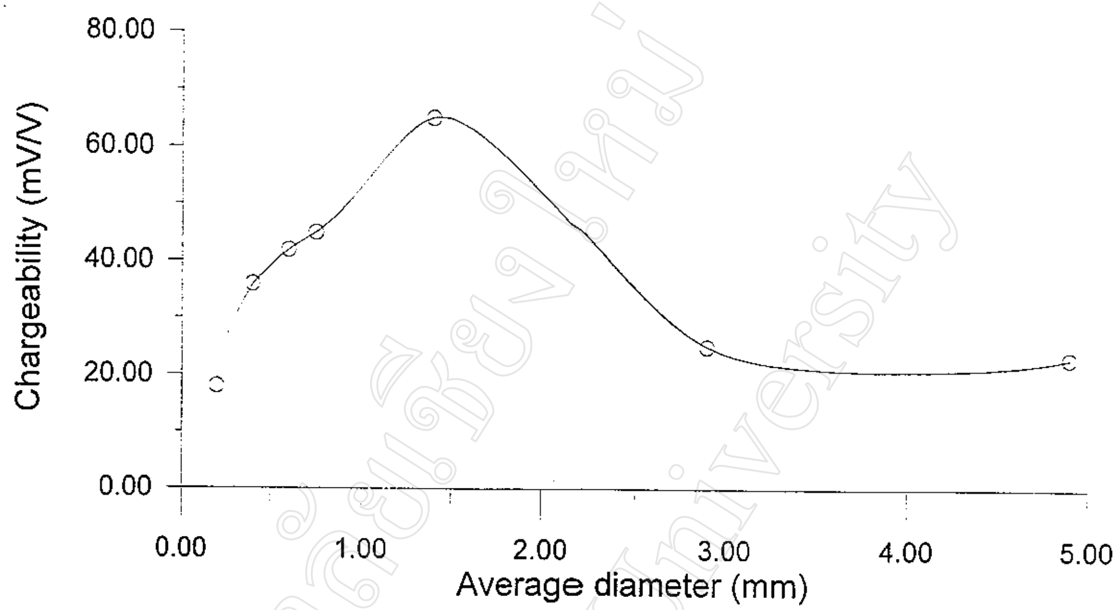


Figure 2.9 Relationship of polarization effect with mineral grain size (modified after Bacon, 1965).

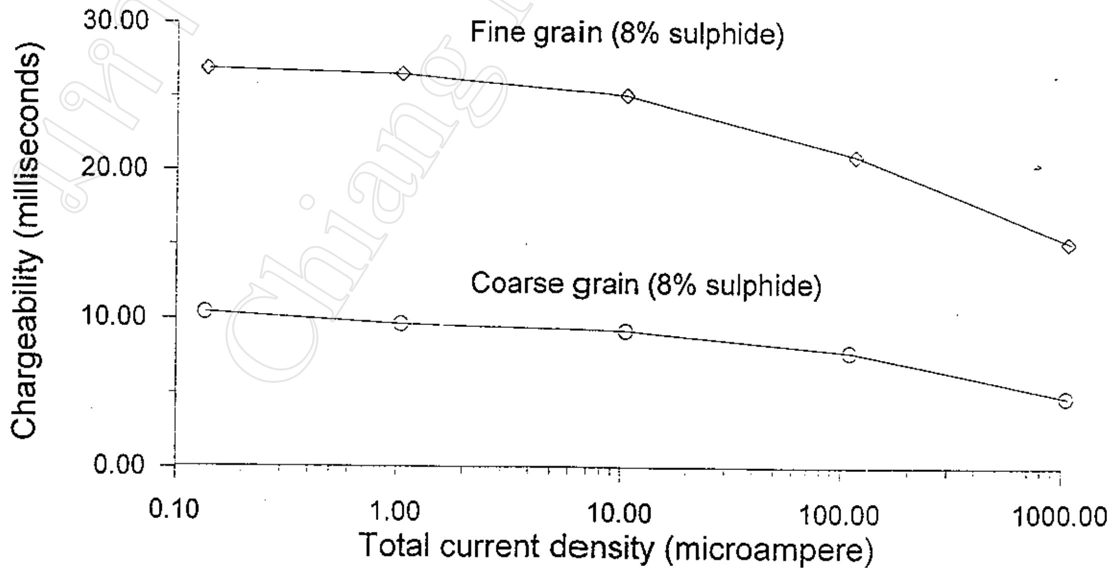


Figure 2.10 Relationship of polarization effect with current density (modified after Scott and West (1969).

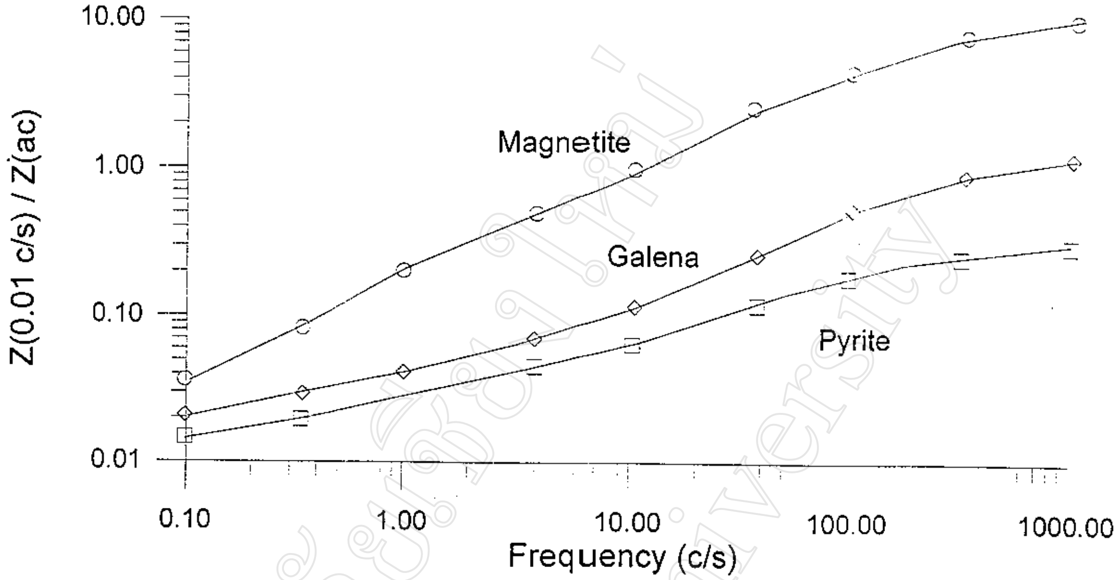


Figure 2.11 Relationship of polarization effect with frequency applied (modified after Keevil and Ward, 1962).

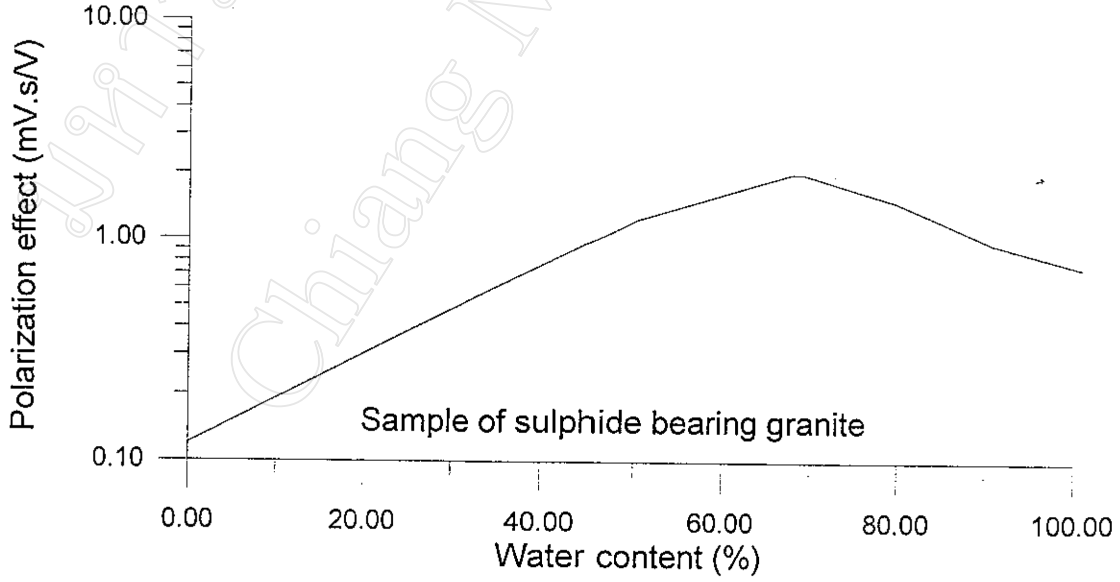
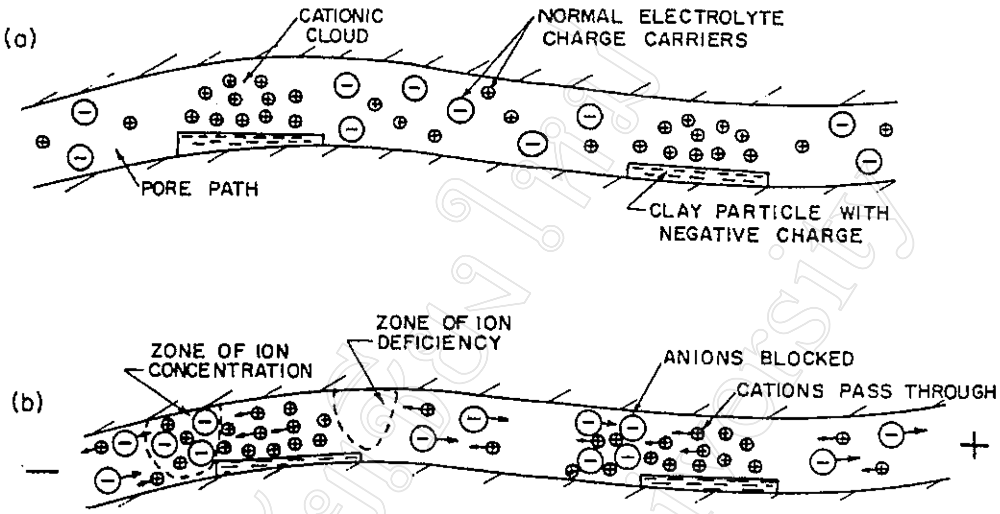
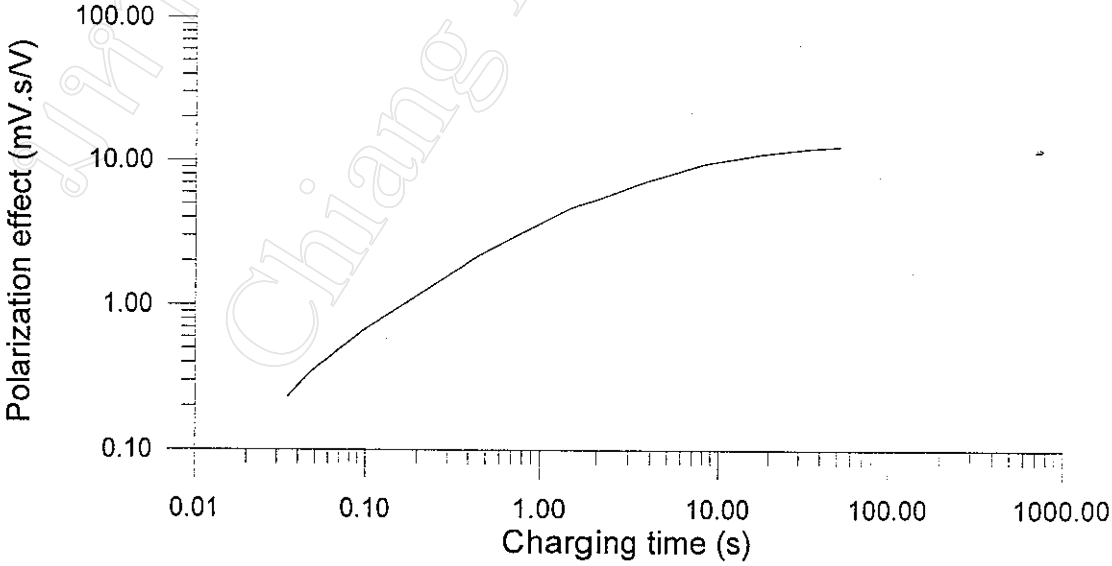


Figure 2.12 Relationship of polarization effect with fluid-filled in pore (modified after Keller and Frischknecht, 1979).



(after Madden and Marshall, 1959)

Figure 2.13 Membrane polarization effect;
(a) without external force, (b) under external force.



(after Anderson and Keller, 1964)

Figure 2.14 Effect of charging time duration on polarization effect.

polarization. Most clay minerals cause this kind of polarization effect, as do some rocks that have high porosity. (after *Madden and Marshall* , 1959; *Keller and Frishchknecht*,1979).

2.3.2 Measurement of induced polarization effect

The induced polarization effect observed is based on the effect of polarization within the ground. By impressing an external electric field continuously and then abruptly cutting off this field, the observed voltage with the potential electrodes across polarizing zone should be zero but it is actually greater than zero and decreases to zero with time. The length of time a charge is applied greatly affects the maximum observed voltage because this artificial force will build up the stored energy in the subsurface bank. If the charging time is short, the resultant polarization effect is incompletely. On the other hand, if the charging time is long, this means a loss of survey time and the cost of the survey will increase. The effect of charging time is shown in Figure 2.15. In practice, the sign of the impressed signal is changed appropriately in time to reduce the effect of electrode accumulation at the current electrode. The current signal in the time domain is illustrated in Figure 2.16(a). The polarization effect measured is the ratio of decay voltage at any time per unit of steady voltage. Figure 2.16(a) shows the conventional method of measuring the induced polarization effect in the time domain. Parameters involved In the time domain are apparent chargeability, M, and metal factor, MF.

The decay curve is measured by integrated decay voltage at some specific length of time. Because a decay curve initially rapid decrease

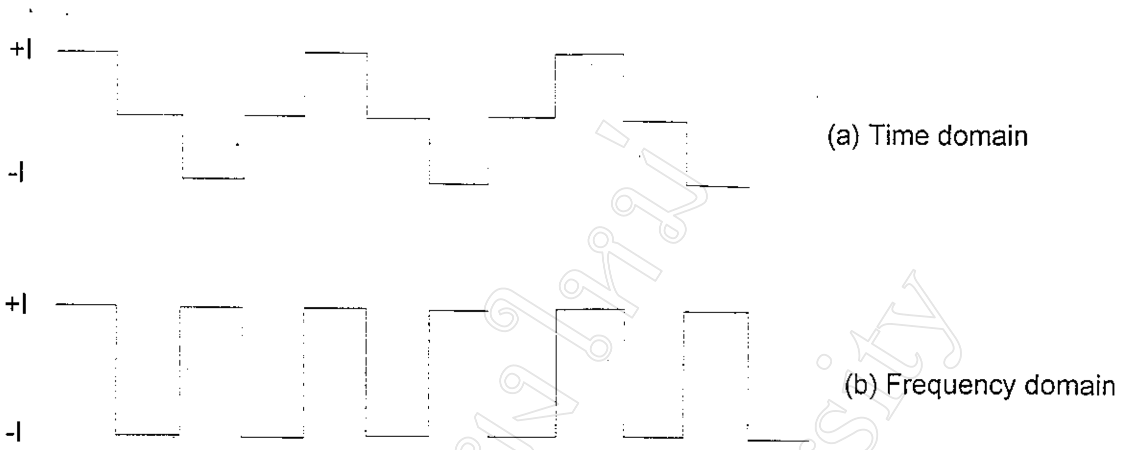


Figure 2.15 Typical current signal used in;
(a) time domain, (b) frequency domain.

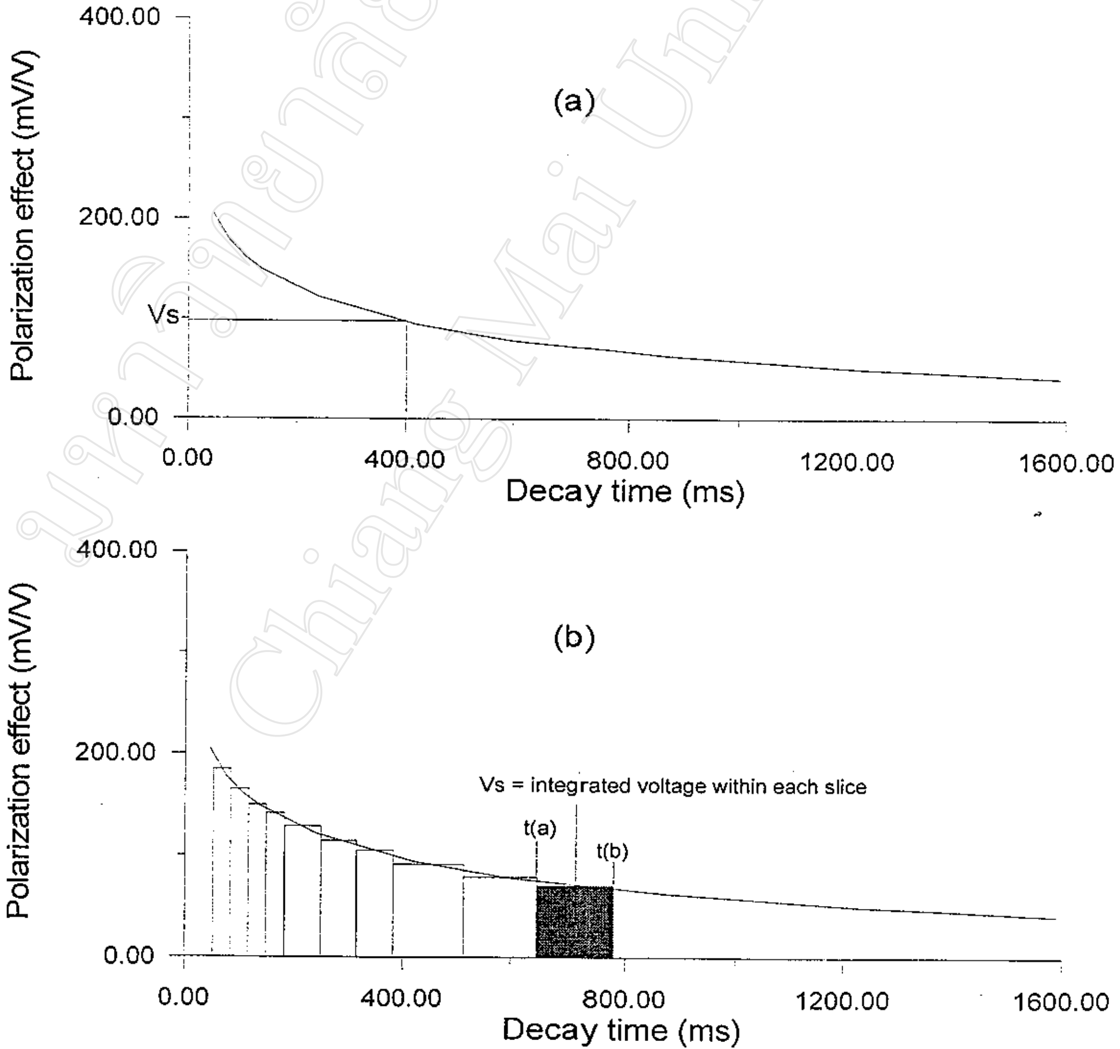


Figure 2.16 Measurement technique in time domain induced polarization
(a) conventional technique and (b) time slice technique.

and then slowly decreases, the instrument used to measure a decay curve has an initial narrow interval and increasingly wider following interval. The method of measuring is shown in Figure 2.15(b). *Bertin and Loeb* (1976) defined of this parameter as *apparent chargeability.* The apparent chargeability, M, is defined by the formula:

$$M = \frac{V_S}{V_P} \quad \text{...(2.3)}$$

$$V_S = \int_{t_1}^{t_2} V_t \, dt \quad \text{...(2.4)}$$

where, V_t is the decay voltage at any time (t) of integration

V_p is primary voltage during current on-time

Substitute (2.4) into (2.3) to obtains apparent chargeability,

$$M = \frac{1}{V_P} \int_{t_1}^{t_2} V_t \, dt \quad \text{...(2.5)}$$

where, t_1 and t_2 are lower and upper limits of integration

The metal factor parameter, MF, describes the relationship of apparent chargeability and apparent resistivity, or normalizing apparent chargeability by apparent resistivity. The relationship is expressed by the formula:

$$MF = \frac{M}{\rho_a} \quad \text{...(2.6)}$$

where, MF is the metal factor in order of 10^5.