Geophysical methods used in groundwater exploration

The role of geophysical methods in Groundwater Exploration is imperative. Its chief aim is to understand the hidden subsurface hydrogeological setting correctly and effectively. As the base of any geophysical methods is the contrast between the physical properties such as the features, objects, and layers and the surroundings.

Parker et al, (2009) indicated that object are only confirmed when the contrast is sufficiently large enough to change the geophysical signal depicting the anomaly as an ‘ alien’ feature of the subsurface i. e., different physical and/or chemical properties than the surroundings in which it is located. They also indicated that geophysical method does not only characterise the subsurface but also spot inhomogeneous features or target that are not characteristics of the surrounding ‘ host’ material in water, water-covered, soil or sediments. Thus the better the contrast or anomaly, the better would be geophysical response and hence the identification. So, the efficiency of any geophysical techniques lies in its ability to sense and resolve the hidden subsurface hydrogeological heterogeneities or disparity.

For groundwater exploration a cautious appliance or combination of techniques is most vital to become successful in exploration, technologically as well as cost-effectively. It is undeniably conceptualized that groundwater cannot be detected directly by any one of the geophysical methods and therefore the interpretation is appropriate and a broad understanding of the subsurface hydrogeological condition or setting is a must. Hubbard S. S et al., (2000), Ugur Yaramanci et al., (2002) and Ramke L. Van Dam (2010) emphasizes the use of two or more complementary geophysical methods to enhance data interpretation. With multiple collocations of geophysical data available, excellent results will be produced with significantly better interpretations than when with a single method.

Conventional geophysical methods have often been used to map the geometry of aquifers such as seismic, electrical and electromagnetic methods (Wattanasen et al (2008)). These methods have been used to determined and estimate locations, transmission properties, storage and the aquifer materials despite the ambiguity of the interpreted results due to limitation in each method and the site dependence. But with the improvements in instruments, the development of better methods as resulted in a widening of its applications.

Surface Electrical Resistivity

The primary purpose of resistivity method is to determine the subsurface resistivity distributions by making measurements on the ground surface. There by measuring the potential difference on the surface due to the current flow within the ground. From this measurement the true resistivity of the subsurface can be estimated. The mechanism responsible for the fluid flow and electric current and conduction in porous media according to P. M Soupious et al., 2007, are generally governed by the same physical parameters and lithological attributes, thus the hydraulic and electric conductivities are dependents on each other, while H. S. Salem et al., 1999, indicated that electric-current conduction is affected by various mechanisms in a saturated systems and can be represented by a two-phase model (grain-matrix conductance) known as dispersed phase, and pore-fluid conductance also known as continuous phase. The two-phase model can further be developed into a five-phase model, consisting of surface conductance occurring at the charged fluid-solid interface, ion-exchange conductance, Maxwellian-effects conductance of both solids in the matrix and those suspended in the pore fluid, grain-matrix conductance and pore fluid conductance.

The electrical conduction in the subsurface is mainly electrolytic because most minerals grains are insulators, therefore, the conduction of electricity is through the interstitial water/ or fluids in the pores and fissures. These pore space and fissure of rocks are filled by groundwater which is a natural electrolyte. The factors responsible for the flow and conduction of electrical resistivity in soil and rocks are extremely variable and can vary by several orders of magnitude. These factors according to Loke, 1999 are porosity, degree of water saturation and concentration of dissolved solids, O. A. L. de Lima et al., 2000; tortuosity and porosity, P. M Soupious et al., 2007; lithology, mineralogy, size, shape, packing and orientation of mineral grains, shape and geometry of pores and pore channels, permeability, compaction, magnitude of porosity, consolidation and cementation and depth and water distribution.

The resistivity of sedimentary rocks, which are usually more porous, with high water content is highly variable with low resistivity and depends on its formation factor. Formation factor is a very powerful tool in resistivity surveys as it allows pore fluid resistivity to be calculated directly from bulk earth resistivity measurements. This relationship can also be used to convert earth resistivity contours in to fluid conductivity or TDS contours.

Bulk resistivity of the ground is measured from direct current resistivity and it obeys an empirical law within an aquifer. This was first proposed by Archie (1942) and the relationship may be expressed as: Ï = a Ï•- m S- n Ïf

Where Ï• is the porosity of the rock formation, S is the degree of saturation, a, m, and n are constants that depend upon the formation, Ïf is the resistivity of pore fluid. Archie's Law shows that bulk resistivity Ï of fully saturated formation of a granular medium containing no clay depends significantly on the resistivity of the pore fluid Ïf. This is mainly as a result of the resistivity of the fluid much lower than that of the solid grains in the matrix. Given that, ' matrix conduction' is negligible and the electric current passes almost entirely through the fluid phase, thus making resistivity methods much more important for hydrological studies. (S. R Wilson et al., 2006). Archie's law can thus be expressed as:

Ï = a Ï•- m Ïf,

assuming that at saturation, S is1.

where Ï is the bulk resistivity, Ïf is the fluid resistivity, Ï• is the porosity of the medium, m is known as the cementation factor and a, the tortuosity factor, cementation intercept, lithology factor or lithology coefficients is associated with the medium and its value in many cases departs from the commonly assumed value of one. It is meant to correct for variation in compaction, pore structure and grain size.

According to H. S. Salem 1999, the cementation factor of Archie; s equation has specific effects on electric conduction processes in porous media and exhibits extensive disparities from sample to sample, formation to formation, interval to interval in the same medium and from medium to medium. Because of its dependence on various properties, m has been referred to as cementation factor, shape factor, conductivity factor, porosity exponent, resistivity factor, and cementation exponent. The dependence of m on the degree of cementation is not as strong as its dependence on the grain and pore properties (shape and type of grains, and shape and size of pores and pore throats). Therefore it is more appropriate to describe m as shape factor instead of cementation factor.

Resstivity survey has been used for a number of geological purposes. S. Srinivas Gowd, 2004, J. O. Oseji, 2006, A. G. Batte et al., 2010, used surface electrical resistivity surveys to delineate groundwater potentials, A. Samouelian et al., 2005, used electrical resistivity survey in soil, S. R. Wilson et al., for saline interface definition, M. Arshad et al., 2006, for lithology and groundwater quality determination, A. Turesson, 2006, for water content and porosity estimations.

S. R Wilson, et al, (2006) applied earth resistivity methods in defining saline interface in Te Horo on the Kapiti Coast in New Zealand. They used vertical electric sounding (VES) and direct current resistivity traversing which has been mostly successful in defining subsurface areas of higher salinity by providing a two-dimensional image of the bulk resistivity structure.

A VES technique has been used most frequently to locate the extent of saline interface using the Schlumberger array geometry. It shows variation in bulk resistivity with distance from the coast and this could be related to the degree of saline mixing but fails to give in depth picture of both the location or structure of the saline interface. However, with the location of the estimated saline interface known, resistivity traversing can be used to improve its location and shape.

They result clearly show the potential of resistivity traversing in mapping and in understanding the structure and progression of saline interface in coastal aquifers. Even though VES data may resolve one-dimensional resistivity structure beneath a sounding location, any two- dimensional interpretation of the data requires interpolation between discrete measurements. In contrast, resistivity traversing data provide continuous two-dimensional image of both lateral and vertical variations in resistivity. The important contrast in the electrical resistivity of saline and fresh water allows direct imaging of a sharp saline interface.

However, they used formation factor to interpret resistivity data from a much wider area. The formation factor for an aquifer is defined from Archie's Law with an assumption that at saturation S is 1, as

F = p/pf= aÏ•-m

Sharma et al (2005), carried out an integrated electrical and very low frequency (VLF) electromagnetic surveys to delineate groundwater- bearing zones in hard rock areas of Purulia districts, west Bangal, in India for the construction of deep tube-wells for large amounts of water.

The location of potential fractures zones in hard rock areas to yield large amounts of groundwater is very difficult and therefore cannot be easily done using one approach. Hence groundwater potential of any location in hard rock areas requires several approaches, geophysical as well as hydrogeological techniques to increase groundwater yield.

Electrical and electromagnetic geophysical methods have been extensively used in the search for groundwater as a result of good correlation between electrical properties, fluid content and geology. Groundwater in hard rock areas is normally found in cracks and fractures and therefore the yield depends on the interconnectivity and size of the fractures.

The combined use of DC resistivity soundings, SP measurement, Wenner profiling and VLF electromagnetic were used to map the fractures in hard rock areas. VES method was used to determined resistivity variations with depth but cannot be performed everywhere without the priori information. The VLF was successful in mapping resistivity contrast in boundaries of fractures with high degrees of connectivity and also as a result of their high resistivity they have been proved to yield a higher depth of penetration in hard rock areas. Additionally, VLF data is useful in determining suitable strike direction to perform resistivity sounding i. e. parallel to strike and thus improving the chances of success. Resistivity profiling and SP measurement also give important information about the presence of a conductivity fracture and groundwater movement.

They concluded that VLF measurement only give indications of the presence of conductive zone but cannot differentiate between deep and shallow sources. Hence, it is essential to follow the location of these VLF anomalies with a technique that investigate the depth of these conductive sources.

Consequently, the Schlumberger sounding technique was proved to be effective in determining resistivity variation with depth.

A review on the use of electrical resistivity survey as applied to soil was carried out by Samoulian et al, (2005) to re-examine the basic concept of the method and the different types of arrays devices used (one-, two- and three-dimensional arrays), the sensitivity of electrical measurements to soil properties which includes the degree of water saturation i. e. water content, arrangement of voids such as porosity and pore size distribution connectivity and the nature of the solid constituents such as particle size distribution and mineralogy and the main advantages and limitations of the method.

They review indicated that electrical resistivity is non-destructive and can make available continuous measurements over a large scope of areas as compared to the conventional soil science measurements and observation which disturb the soil by random and or regular drilling and sampling. As a result of these temporal variables such as water and plant nutriment, depending on the internal structure can be monitored and quantified without changing the soil structure. Thus the application is numerous which includes; determination of soil horizonation and specific heterogeneities, follow-up of the transport phenomena and the monitoring of solute plume contamination in a saline or waste context. However, they suggested that electrical measurements do not give straight access to soil characteristics that is of interest to the agronomist and therefore preliminary laboratory calibration and qualitative or quantitative data interpretations must be carried out in order to connect the electrical measurements with the soil characteristics and function.

Direct and indirect method of groundwater investigation was carried out in southern Sweden using magnetic resonance sounding (MRS) and vertical electrical sounding (VES) by Wattanasen et al, (2008). The aim of the survey was to compare MRS with VES and other geophysical methods. The MRS results were consistent with VES. It is a successful tool in groundwater exploration particularly in an area of sedimentary rocks of high magnitude of earth magnetic field. A good quality data was obtained as a result of low ambience noise, low variation in the earth magnetic field and high level of MRS signal. The MRS was effective in determining the depth to water layers, water content and their thickness. It can also detect water in areas with high conductive clay layer that is close to the surface, a factor that limits the penetration depth of other geophysical methods like GPR.

Hydraulic properties are essential parameters in hydrogeology for accurate modelling of groundwater flow and rate of movement of contaminant or pollution. These properties; hydraulic conductivity, transmissivity and storage coefficient are used to describe and quantify the capacity of the materials composing aquifers and confining units to transmit and store water. The hydraulic conductivity and storage coefficients (storativity) are aquifer properties that may vary spatially because of geologic heterogeneity.

Traditionally, pumping test or laboratory techniques when core samples are available have been used to determine the aquifer hydraulic parameters. These methods have been proved to be invasive and expensive and provide information only in the vicinity of the boreholes and the sample locations. The application of geophysical techniques could be seen as a means of providing important complementary information that might help to reduce the costs of hydrogeological investigations.

Aristodemou et al., (1999) and Soupious et al., (2007) also applied surface geophysical techniques to determine the hydraulic conductivity values using both Kozeny-Carman-Bear equation and the Worthington equation.

According to Worthington equation: Fa= Fi .(1 + BQvÏw)- 1 (1)

where, Fa is the apparent formation factor, Fi is the intrinsic formation factor and the BQv term is related to the effects of surface conductance, mainly due to clay particles. In case surface conductance effects are non-existent, the apparent formation factor becomes equal to the intrinsic one. Thus, 1/Fa= 1/Fi +(BQv/Fi)Ïw (2)

Where 1/Fa, is the intercept of the straight line and BQv/Fi represents gradient. Thus, by plotting 1/Fa versus fluid resistivity Ïw, we should in principle, obtain a value for the intrinsic formation factor, which will subsequently enable us to estimate porosity from the formula

Ïo = a Ïw Ï•- m where Ïo is the bulk resistivity, Ïw is the fluid resistivity, Ï• is the porosity of the medium and m is the cementation factor, although it is also interpreted as grain-shape or pore-shape factor; the coefficient of a is associated with the medium and its value in many cases departs from the commonly assumed value of one.

The apparent formation factor Fa = Ïo/Ïw, where Ïo is the bulk resistivity obtained from the resistivity inversion and Ïw is the fluid electrical resistivity obtained from the borehole.

These porosities were subsequently used to estimate the hydraulic conductivity through the Kozeny-Carman-Bear equation.

K = (Î´wg / Î¼) . (d2 /180) . [(Ï•3 / (1 – Ï•2)]

Where d is the grain size, Î´w is the fluid density, and Î¼ is the dynamic viscosity.

Andreas Hordt et al., (2006) and Andrew Binley et al., (2005) used spectra induced polarization to determine the hydraulic conductivity. There work was focussed on laboratory experiments in order to establish a semi- empirical relationship between complex electrical resistivity and hydraulic parameters and then applied the field technique to evaluate the feasibility of the method.

Thus the hydraulic conductivity, k was then calculated from the Kozeny-Carman equation based on formation factor and inner surface area.

K = 1/ F(Spor)c,

The exponent c is an adjustable parameter.

Complex electrical conductivity was used as a convenient means of hydrogeological applications;

Ïƒ = â”‚Ïƒâ”‚ eiÏ• = Ïƒ’ + iÏƒ”

Where Ïƒ’ and Ïƒ” denote real and imaginary part, and â”‚Ïƒâ”‚ and Ï• denote magnitude and phase, of the conductivity Ïƒ.

Formation factor was calculated from the equation:

F = Ïƒ w/ Re(Ïƒ) – Im (Ïƒ)/l

where Ïƒw is the pore fluid conductivity. The factor l is the ratio between imaginary and real part of the surface conductivity.

The pore space- internal surface area, Spor is an empirically derived equation from laboratory.

Anita Turesson (2006), applied ground- penetrating radar and resistivity independently to evaluate their capability to assess water content and porosity for saturated zone in a sandy section, since dielectric and the resistivity of rocks and sediments are very much dependent on moisture content. Archie’s empirical formula was used in the resistivity method to determine the relationship between resistivity and porosity (Andrew Binley et al., 2005) in the sedimentary clay free rocks based on the formation factor, which is the ratio of resistivity of the porous media to that of the pore fluid. The results obtained shows good agreement between the two methods in the saturated zone and they use of the independent methods greatly strengthen the results.

Another subsurface geophysical techniques is the Induced Polarization (IP) technique which over the past years has been used successfully for mineral exploration by providing in situ information about rock mineralogy mainly disseminated ores and mineral discrimination. More recently the method has been applied in the field of environment and engineering studies to materials which do not contain conductive minerals but rather clay minerals for the mapping of polluted land areas, movement of contaminants and grain size distribution parameters in unconsolidated sediments (E. Aristodemou et al., (2000); Andreas Hordt et al., 2006, 2007)).

In theory, induced polarization is a dimensionless quantity whereas in practice it is measured as a change in voltage with time or frequency. The time and frequency IP methods are fundamentally similar, however, they differ in a way of considering and measuring electrical waveforms. In the former, a direct current is applied into the ground, and what is recorded is the decay of voltage between two potential electrodes after the cut off of the current (time-domain method). In the latter, the variation of apparent resistivity of the ground with the frequency of the applied current is determined (frequency-domain method). In another type of frequency method, which is called Complex Resistivity (CR) method, a current at frequency range (0. 001 Hz to 10 kHz) is injected in the ground and the amplitude of voltage as well as its phase with respect to the current is measured. That is a phase-angle IP measurement.

Various studies have been carried out most recently to establish an empirical relationship between hydraulic properties and induced polarisation measurements, though only limited number of studies exists so far at a field scale. The reason for this is that hydraulic properties depend on both porosity and geometry of the pore space.

Induced polarisation (IP), is the only geophysical methods that depends on surface characterisation and has been used in hydrology as the possible link to hydraulic properties. (Binley et al., (2005)).

Semi-emperical relationships between IP and hydraulic properties have been extensively investigated. Andreas Hordt et al., (2007), estimated hydraulic conductivity from induced polarisation using multi-channel surface IP measurement over a sand/gravel aquifer at Krauthausen. Despite carrying out measurement over a broad frequency range called spectra IP, the hydraulic conductivity analysis was restricted to single frequency data based on the Borner model and Slater and Lesme model. They however, used two different approaches to determine the hydraulic conductivities from the IP results. The first approach is the Börner method refered to as the constant-phase angle (CPA), where real and imaginary parts of complex electrical conductivity was sufficient to estimate the hydraulic conductivity from the Kozeny-Carman type equation; k= 1/F(Spor)c, based on two parameters; the formation factor and the pore-space related internal surface area, Spor which was empirically derived from laboratory measurements .

The second approach suggested by Slater and Lesme was based on an empirical relationship between k and the imaginary part of conductivity at 1 Hz without using the real part and/or the formation factor:

K= m/(b”)n. This was based on the argument that hydraulic conductivity primarily depends on the specific inner surface.

Andrew Binley et al. 2005, worked on the relationship between spectra induced polarisation and hydraulic properties of saturated and unsaturated sandstone. They tried to observe the spectra IP response of samples taken from the UK sandstone aquifer and compared the measured parameters with the physical and hydraulic properties. There result shows that the mean relaxation time, Æ¬, is a more suitable measure of IP response for these sediments, with a significant inverse correlation existing between the surface area to pore volume ratio and the Æ¬, suggesting that Æ¬ is a measure of a characteristic hydraulic length scale. This was supported by a strong positive correlation between log K and log Æ¬. There results revealed significant impact of saturation on the measured spectra, thus limiting the applicability of hydraulic-electric models in utilizing the SIP measurements. However, in contrast, they suggested new opportunities for development of physically based models linking unsaturated hydraulic characteristics with spectra IP data.

The resistivity method was used to solve more problems of groundwater in the types alluvium, karstic and another hard formation aquifer as an inexpensive and useful method. Some uses of this method in groundwater are: determination of depth, thickness and boundary of an aquifer (Zohdy, 1969; and Young et al. 1998), determination of interface saline water and fresh water (El-Waheidi, 1992; Yechieli, 2000; and Choudhury et al., 2001), porosity of aquifer (Jackson et al., 1978), water content in aquifer (Kessels

Induced Polarization

Fundamentals

The induced polarization (IP) method is an electrical geophysical technique, which measures the slow decay of voltage in the subsurface following the cessation of an excitation current pulse.

Basically, an electrical current is imparted into the subsurface, as in the electrical resistivity method explained elsewhere in this chapter. Water in the subsurface geologic material (within pores and fissures) allows for certain geologic material to show an effect called “ induced polarization” when an electrical current is applied. During the application of the electrical current, electrochemical reactions within the subsurface material takes place and electrical energy is stored. After the electrical current is turned off the stored electrical energy is discharged which results in a current flow within the subsurface material. The IP instruments then measure the current flow.

Thus, in a sense, the subsurface material acts as a large electrical capacitor.

The induced polarization method measures the bulk electrical characteristics of geologic units; these characteristics are related to the mineralogy, geochemistry and grain size of the subsurface materials through which electrical current passes.

Induced polarization measurements are taken together with electrical resistivity measurements using specialized IP instruments. Although the IP method historically has been used in mining exploration to detect disseminated sulfide deposits, it has also been used successfully in ground water studies to map clay and silt layers which serve as confining units separating unconsolidated sediment aquifers.

Advantages

Induced polarization data can be collected during an electrical resistivity survey, providing the proper equipment is used. The addition of IP data to a resistivity investigation improves the resolution of the analysis of resistivity data in three ways: 1) some of the ambiguities encountered in resolving thin stratigraphic layers while modeling electrical resistivity data can be reduced by analysis of IP data; 2) IP data can be used to distinguish geologic layers which do not respond well to an electrical resistivity survey; and 3) the measurement of another physical property (electrical chargeability) can be used to enhance a hydrogeologic interpretation, such as discriminating equally electrically conductive targets such as saline, electrolytic or metallic-ion contaminant plumes from clay layers.

Limitations

The induced polarization method is more susceptible to sources of cultural interference (metal fences, pipelines, power lines, electrical machinery and so on) than the electrical resistivity method. Also, induced polarization equipment requires more power than resistivity-alone equipment – this translates into heavier and bulkier field instruments. The cost of an IP system can be much greater than a resistivity-alone system. This, plus an added amount of complexity in the interpretation of the IP data and the expertise needed to analyze and interpret this data may exceed the resources of some contractors and consultants.

Induced polarization fieldwork tends to be labor intensive and often requires two to three crew members. Like electrical resistivity surveys, induced polarization surveys require a fairly large area, far removed from power lines and grounded metallic structures such as metal fences, pipelines and railroad tracks.

Instrumentation

Induced polarization instruments are similar to electrical resistivity instruments. There are two different types of induced polarization systems. Probably the most common type of IP instrument is the " time-domain" system. This instrument transmits a constant electrical current pulse during which time the received voltage is sampled for an electrical resistivity measurement, acting like a conventional electrical resistivity system. The electrical current is then shut off abruptly by the system, and after a specified time delay (several milliseconds) the decaying voltage in the subsurface is sampled at the IP receiver, averaging over one or more time windows or " time gates." The units of measurement are in millivolt-seconds per volt.

The second type of IP instrument is the " frequency-domain" system. In this type of system, transmitted current is sinusoidal at a specified frequency. Since the system is always on, only an electrical resistivity measurement can be collected at a particular frequency. To collect induced polarization data, two frequencies are used, and a percent change is apparent electrical resistivity from measurements collected at the two frequencies is calculated. This number is called the " percent frequency effect" or " PFE," and the units are dimensionless in percent. Two frequencies commonly used are 0. 3 and 3. 0 Hertz, representing low and high frequency responses, respectively.

Other types of Induced polarization may be encountered, although not commonly in environmental applications. These include “ spectral induced polarization,” “ complex resistivity,” and “ phase” systems. A detailed description of these systems is beyond the scope of this chapter and the reader is advised to consult the literature for an extensive discussion of these systems.

Electrical resistivity surveying is an active geophysical technique that involves applying an electrical current to the earth and measuring the subsequent electrical response at the ground surface in order to determine physical properties of subsurface materials. The general principle of resistivity testing is that dissimilar subsurface materials can be identified by the differences in their respective electrical potentials. Differences in electrical potentials of materials are determined by the application of a known amount of electric current to these materials and the measurement of the induced voltage potentials. Ohm’s law states that the voltage (V) of an electric circuit is equal to the electric current (I) times the resistivity (R) of the medium (V-IR). Resistivity surveys are conducted by: 1) applying a known amount of electric current (I) to the earth; 2) measuring the induced voltage (V) ; and, using these two measurements, 3) determining the resistivity (R) of the volume of earth being surveyed.

Resistivity methods usually require that both current inducing and measurement electrodes to be pushed or driven into the ground. With connecting wires from the instruments to the electrodes, electrical current is introduced into the ground using the current electrodes and resistivity measurements are performed using different measurement electrode configurations and spacings. There are a number of standardized testing procedures, some of which are described in detail in this section.

Resistivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer that exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i. e., salinities) will appear to be more than one geoelectric layer. The interpretation of resistivity data is therefore best made in conjunction with other geophysical techniques (i. e., seismic refraction) or conventional subsurface investigations (i. e., soil borings

Historically, it was the use of galvanic measurement systems that gave rise to the IP method which demonstrated its high efficiency in resistivity surveys for mineral prospecting and structural applications. Induced polarization is a complex phenomenon controlled by many physical and physicochemical reactions associated with passage of current through rocks.

The Induced Polarization method of geophysical exploration is something of a rarity. It is the only “ new” geophysical method to come into use in over fift