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Applications of Geophysical Methods for Subsurface Geological and Geotechnical Assessment - An Overview

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Abstract:- The Geophysical methods involve investigations on the surface with the aim to delineate subsurface details. This is achieved by measuring certain physical properties and interpreting them in terms of subsurface geological features. A number of geophysical methods like Seismic refraction, Seismic reflection, Seismic tomography, Multi-Channel Analysis of Surface waves (MASW), Ground Penetration Radar (GPR), Resistivity, Self-Potential (SP), Magnetic, Gravity and Well Logging methods are available. These methods can be employed to solve various geotechnical engineering problems such as Subsurface characterization, Engineering properties, Highway subsidence, Ground water delineation, Health study of dams, Phreatic surface determination, Seepage detection and Locating buried manmade objects. The present paper discusses about different available geophysical methods, its applications and limitations. Many-a- time's single geophysical methods may not yield the desired result due to their limitations. In such cases two or more methods can be integrated for better understanding of subsurface.

Keywords:- *Site Characterization, Geophysical Methods, Geological Assessment Geotechnical Engineering Problems.*

I. INTRODUCTION

The geophysical methods have been applied and accepted for geotechnical engineering problems since decades. Obviously, the focus has been on geotechnical projects using geophysical methods to investigate the complex subsurface as a base for large engineering structures such as dams, bridges and buildings. The review focuses mostly on all geophysical methods for geotechnical engineering application and limitations. Recently several modern geophysical methods have been adopted for geotechnical investigation in various fields. They help to improve the quality of imaging the subsurface geological layers and detect even small variations in subsurface features (Anderson, N.L., 2006). Use of integrated Seismic Refraction Survey, Electrical Resistivity Survey and Ground Penetrating Radar (GPR) methods for selection of bridge alignment amongst two alternatives. Earlier, conventional seismic reflection and electrical resistivity geophysical methods were common and used in pre-feasibility applications (E Martinho and A Dionísio, 2014). The geophysical methods can be used in different stages such as feasibility, design, construction and post-construction. Choice and selection of available geophysical methods is based the stage of applications, objective and based on advantage and limitations of each methods (CSMRS Booklet, 1992).

In this paper, an attempt has been made to summarize the different geophysical methods used in geotechnical applications, their principle, its applications and limitations for better understanding.

II. SEISMIC METHODS

Seismic methods involve measuring the propagation of seismic waves through earth materials.

➢ *Seismic Refraction Method*

Seismic refraction involves measuring the travel time of the component of seismic energy which travels down to the top of rock (or other distinct density contrast), is refracted along the top of rock, and returns to the surface as a head wave along a wave front. The waves which return from the top of rock are refracted waves, and for geophones at a distance from the shot point, always represent the first arrival of seismic energy. Seismic refraction is generally applicable only where the seismic velocities of layers increase with depth. Therefore, where higher velocity layers may overlie lower velocity layers, seismic refraction may yield incorrect results (IS 15681: 2006). In addition, since seismic refraction requires geophone arrays with lengths of approximately 4 to 5 times the depth to the density contrast of interest (e.g. the top of bedrock), seismic refraction is commonly limited to mapping layers only where they occur at depths less than 50 m. Greater depths are possible, but the required array lengths may exceed site dimensions, and the shot energy required to transmit seismic arrivals for the required distances may necessitate the use of very large explosive charges. Seismic refraction surveys very important role in geotechnical engineering applications (Romero-Ruiz et al., 2019).

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Application of Seismic Refraction method for Geotechnical Engineering studies		
S. No	**Primary application**	**Secondary application**
1	Mapping lithology (< 50 m depth)	Mapping lithology (> 50 m depth)
2	Construction material surveys	Mapping ground water cones of depression
3	Determining volume of organic materials in filled in lakes or karst features.	Mapping bed rock topography (>50 m depth)
4	Mapping bed rock topography (<50 m depth)	Mapping sub-bedrock structure
5	Delineating steeply dipping geological contacts (< 50 m depth)	Delineating steeply dipping geological contacts (> 50 m depth)
6	Identifying regions of potential weakness (shear zones and faults < 50 m depth	Identifying regions of potential weakness (shear zones and faults > 50 m depth
7	Identifying near surface karstic sinkholes and the lateral extent of their chaotic, brecciated and otherwise disrupted ground	Mapping air-filled cavities, tunnels (>50 m depth)
8	Estimating rippability	Mapping filled cavities, tunnels
9	Foundation integrity studies	Mapping archeological sites (buried Ferro-magnetic, nonmagnetic excavation, burials, etc.)
10	Dam-site integrity studies	Mapping locating landfills
11	Determining in situ dynamic rock properties (Young's modulus and Poisson ratio)	Mapping major discontinuities orientation (near surface bedrock)
12	Mapping abandoned in-filled open-pit mines and quarries (<50 m depth)	Landslide site evaluation

➢ *Seismic Reflection Method*

Seismic reflection involves imaging the sub-surface layers using artificially generated seismic waves. Typically, small dynamite explosions or vibratory sources are used to generate seismic waves at or near the surface. Receiving devices (geophones) are placed on the surface to detect the seismic energy that originates from the seismic source, which travels down into the earth and gets partially reflected back to the surface at each geological boundary. 2D seismic exploration involves acquiring seismic data along a single line of receivers. The resultant 2D seismic image can be used to detect features in the subsurface along the particular survey line. 3D seismic exploration involves using a grid of surface receivers to detect the reflected seismic energy generated by each seismic source. 3D seismic data yields a much more extensive and higher-resolution image of the subsurface than 2D seismic data. This makes 3D seismic more attractive in terms of being able to contribute significantly to the structural and Stratigraphy understanding of a mine and oil & gas area. The shallow seismic reflection method has been found a significant range of from engineering to ground water exploration and geotechnical studies (Sharma PV, 1986)

Application of Seismic Refection method for Geotechnical Engineering studies		
S. No	**Primary application**	**Secondary application**
1	Mapping lithology (> 50 m depth)	Mapping lithology (< 50 m depth)
2	Determining volume of organic materials in filled in lakes or karst features	Mapping ground water cones of depression
3	Mapping bed rock topography (>50 m depth)	Identifying regions of potential weakness (shear zones and faults < 50 m depth)
4	Mapping sub-bedrock structure	Mapping air-filled cavities, tunnels (<50 m depth)
5	Delineating steeply dipping geological contracts (> 50 m depth)	Detecting abandoned mines shafts
6	Identifying near surface karstic sinkholes and the lateral extent of their chaotic, brecciated and otherwise disrupted ground	
7	Mapping air-filled cavities, tunnels (>50 m depth)	
8	Mapping filled cavities, tunnels	
9	Mapping abandoned in-filled open-pit mines and quarries (>50 m depth)	
10	Mapping abandoned underground mines (>50 m depth)	

➢ *Cross- hole seismic tomography (CST)*

Seismic tomography can be defined as the determination of the spatial variation of acoustic velocity from external measurement of a parameter that is influenced by that property by way of a line integral relationship (De Benedetto, et al., 2012). CST method is performed by lowering source & receiver in two different boreholes and generating both P-waves and S-waves. The objective of a seismic tomography consists of knowledge of a subject medium through seismic rays to consequently plot a map of seismic wave propagation velocities. The method has proven to be useful for solution with high resolution P-and S-wave velocity data for wide range of geotechnical engineering applications. In the cross- hole tomography, the source and receivers operate closely to the investigated structure and are not distorted by traveling through highly heterogeneous and

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attenuated near subsurface layers (Mikhail Lebedev, and Kirill Dorokhin, 2013). These methods involve measuring the travel times and amplitudes of seismic energy P and S waves in terms of acoustic velocity is a function of elastic moduli and density (IS 13372 (Part 2): 1992).

Application of Cross hole Seismic tomography method for Geotechnical Engineering studies		
S. No	**Primary application**	**Secondary application**
1	Mapping lithology with high resolution	Mapping abandoned underground mines
2	Foundation integrity studies with high resolution	Detecting abandoned mines shafts
3	Mapping bed rock topography with high resolution	Mapping fracture orientation (near surface bedrock)
4	Identifying regions of potential weakness (shear zones and faults up to 100 m depth)	Locating buries drums, pipelines, and other Ferro-magnetic, nonmagnetic objects
5	Mapping filled cavities, tunnels with high resolution	Estimating in situ rock properties (Saturation, porosity, permeability)
6	Dam-site integrity studies with high resolution	Mapping abandoned in-filled open-pit mines and quarries
7	Determining in situ dynamic rock properties (Young's modulus and Poisson ratio)	-

➢ *Multi-Channel Analysis of Surface Waves (MASW)*

The multi-channel analysis of surface waves (MASW) method was first introduced into geo-technical and geophysical community by (Momayez, et al., 2013) although earlier development versions came out several years prior. Multichannel Analysis of Surface Waves (MASW) method gives the shear velocity (Vs) in the depth range of 0 to 30 m. It involves measurement of arrival times of seismic surface waves generated from seismic sources at predetermined pattern and analyses the propagation velocities. Interpretation of data requires software's to produce profile of Vs variations in 1D/2D/3D.

The application of this technique includes Soil-bed rock mapping, seismic site characterization and evaluation of bearing capacity, compaction, grouting and also the efficacy of any ground improvement method. Equipment for MASW includes multichannel analysis seismograph (24-channel or higher), 4.5 Hz geophones, cable with takeout at 5 m spacing, power source can be 12V car battery and seismic source can be sledge hammer or weight drop. Interpretation of the data requires software and trained person to generate shear wave velocity profiles (Alex Varughese, et al., 2017).

Application of MASW method for Geotechnical Engineering studies		
S. No	**Primary application**	**Secondary application**
1	Seismic Site Characterization	Detection and monitoring of areas of insufficiently dense subbase
2	Foundation integrity studies (<30 m)	Mapping abandoned in-filled open-pit mines and quarries
3	Dam-site integrity studies (<30 m)	Landslide site evaluation
4	Evaluation of ground improvement methods such as compacting, grouting etc.	Mapping archeological sites (buried Ferro-magnetic objects)
5	Bed rock mapping (<30 m)	Determining in situ dynamic rock properties (Young's modulus and Poisson ratio) – with P-wave data

III. ELECTROMAGNETIC METHOD- GROUND PENETRATION RADAR (GPR)

Ground penetrating radar (GPR) is a high resolution electromagnetic methods that is designed primarily to investigate the shallow subsurface of the earth, building material, and road and bridges (Baker, G.S., et al., 2007). Senthil et.al., 2021 has presented comprehensive study on different applications of GPR such as utility detection, bed rock delineation and dam health investigations. GPR utilizes propagating EM waves that respond to changes in the electromagnetic properties of the shallow subsurface. The propagation velocity of EM waves, which is the principal controlling factor on the generation of reflections, is determined by the relative permittivity contrast between the background material and the target (or the contrast between layers). Relative permittivity is defined as the ability of a material to store and then permit the passage of EM energy when a field is imposed on the material and can be measured in the laboratory or in-situ. A typical GPR unit consists of a transmitting and receiving antenna, where the transmitting antenna generates an EM pulse that travels into the subsurface and then reflects off an interface or scatters off point sources (both caused by a contrast in relative permittivity). This reflected/scattered energy then travels back to the surface, where it is recorded by the receiving antenna. The time it takes for the wave to travel down to an interface and back up to the surface is called the travel time, and it is used to determine the in-situ propagation velocity of the subsurface material. The velocity (distance/travel time) for an EM wave in Earth's atmosphere at or near sea level is 0.33 m/ns. Because the relative permittivity of all earth materials is greater than the permittivity of air, the velocity of an EM wave in all earth materials will be less than the EM propagation velocity in air - typical materials range between 0.05 and 0.15 m/ns.

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Although the propagation velocity of an EM wave is dependent on the relative permittivity of the material, the amplitude and attenuation of a propagating wave is dependent on the magnetic permeability and the electrical conductivity of the material. Magnetic permeability is the ability of the material to become magnetized when an EM field is imposed on the material. As magnetic permeability increases, amplitude attenuation increases; therefore, increased magnetic permeability results in poorer data quality and/or penetration depth. Electrical conductivity also affects the propagation of EM waves. Materials with a high electrical conductivity tend to attenuate EM signals; therefore, highly conductive materials will produce poor GPR data and/or reduce penetration depth. GPR method explanation of the critical variables, parameters, and principle equations that dictate how EM waves behave and respond to changes in subsurface electromagnetic properties (Dobrin, B.M., et al., 1988).

Application of GPR method for Geotechnical Engineering studies		
S. No	**Primary application**	**Secondary application**
1	Locating underground utilities such as drums, pipelines, and other Ferro-magnetic objects	Mapping water-filled cavities, tunnels
2	Mapping archeological sites (buried Ferro-magnetic, nonmagnetic excavation objects)	Landslide site evaluation
3	Detection of voids beneath pavement	Mapping abandoned in-filled open-pit mines and quarries
4	Detection and delimitation of zones of relatively thin subgrade base course material	
5	Detection of bodies of subgrade in which moisture content is anomalously high as a precursor to development of pitting and potholes	
6	Bed rock delineation depth <30 m	
7	Foundation integrity studies depth <30 m	
8	Dam-site integrity studies depth <30 m	

IV. ELECTRICAL METHOD

The electrical methods are used to decipher the subsurface information using variation in resistivity values of different litho-units.

- *Electrical Resistivity method/ Resistivity Imaging*

Electrical resistivity is a fundamental property of a material that measure how strongly it resists electric current. The principle of resistivity method is measuring subsurface variation in electrical resistivity (Reynolds, J.M., 2011). In resistivity method the current is driven through the ground using a pair of electrodes and the resulting distribution of the potential in the ground is mapped by using another pair of electrodes connected to sensitive voltmeter. From the magnitude of the current applied and from the knowledge of the current electrode separation it is possible to calculate the potential distribution and also the path of the current flow if the underground were homogeneous (Birendra Pratap et al. 2014). In highly conductive material, the resistivity method investigation depth is limited (IS 15736: 2007).

Application of Resistivity method for Geotechnical Engineering studies		
S. No	**Primary application**	**Secondary application**
1	Mapping the ground water aquifer layers	Mapping lithology (< 100 m depth)
2	Determining volume of organic materials in filled in lakes or karst features	Estimation clay minerals
3	Determining water depths (including bridge scour)	Subsurface fluid flow
4	Mapping ground water cones of depression	Mapping bed rock topography (up to100 m depth)
5	Mapping contaminate in the ground	Identifying near surface karstic sinkholes and the lateral extent of their chaotic, brecciated and otherwise disrupted ground
6	Mapping crop land salination and desalination over time	Mapping filled cavities, tunnels
7	Delineating steeply dipping geological contacts (< 100 m depth)	Dam-site integrity studies
8	Identifying regions of potential weakness (shear zones and faults < 100 m depth	Mapping locating landfills
9	Mapping salinity ingression in coastal areas	Mapping abandoned in-filled open-pit mines and quarries
10	Landslide site evaluation	Mapping abandoned underground mines & shafts
11	Estimating in situ rock properties (Saturation, porosity, permeability)	

- *Self- Potential Method (SP)*

S.P. method is also an electrical method and combination with resistivity method used for detecting flow paths. SP is resistivity method used in combination with resistivity method for detecting sub surface flow paths. SP method measures the natural ground potentials that are produced by electrochemical action (Electrons moving in material) in the surface rocks (Anderson et al., 2006).

The origin of self – potentials may be from i) Background potentials, ii) Mineralization potential. The background potential may originate in several ways, due to variation in the soil chemistry, variation in electrolytic connection in the ground water, and other electrochemical phenomena. The potential differences occur naturally within the Earth and can be measured (Unit is volt). The most accepted theory for sulfides suggests that the portion of the ore body above the water table is being oxidized (losing electrons) while the portion below is being reduced, setting up a flow of electrons from one end of the ore body to the other. This theory cannot explain anomalies where the ore body is completely below the water table, explain why a clay overburden prevents a self-potential from forming, or explain how self-potentials form in poor conductors. The major advantage of the SP methods is to map the subsurface fluid flow such as seepage path in embankment dams, grouting and contamination flow path etc for geotechnical problems.

- *Induced Polarization (IP)*

The electrical conduction in most rocks is essentially electrolytic, by transport of ions through interstitial water in pores. However, when a current is passed through a rock containing metallic minerals, the ionic conduction is hindered to a considerable extent by the mineral grains in which the current flow is electronic. This leads to an accumulation of ions at the interface between the mineral and solution, resulting in a growth of electrochemical voltage at the metallic grain surface. The process is similar to electrode polarization that occurs at the surface of metal electrodes dipped in an electrolyte. When the externally applied current is switched off, the electrochemical voltage is dissipated, but does not drop to zero instantaneously. The decay in voltage is observed to vary with time and can be measured as a fraction of voltage V that existed when the current was flowing. The ratio V/v gives a measure of the concentration of metallic minerals in rock in the rock formation (Sharma PV, 1986). IP method majorly applied in mineral exploration and geotechnical and environmental problems.

V. MAGNETIC METHOD

Magnetic methods have a long history behind them. Early studies of the magnetism of rocks started with the discovery of the magnetite rich rock, and idea that the earth itself acts as a magnet. The methods of prospecting the study of the magnetic properties of rocks became increasingly important. According to Lenz's law when a substance is placed in a magnetic field, little extra currents are generated inside the atoms by a process called induction. These currents produce a magnetic field opposite in direction to the applied field. This induced field is called the Intensity of Magnetization (I) and is proportional to the applied field. $\mathbf{I = kH}$

k is called the magnetic susceptibility of the substance, I- Magnetization, H- external magnetic field.

Magnetic method prospecting to variation of magnetic properties of rocks such as variation in distance to magnetic body (including relief in basement rocks), difference in magnetic susceptibility (how easily rocks magnetized), Magnetic susceptibility is very low for most materials; only high for ferromagnetic substances, Susceptibility of rocks is primarily controlled by the amount of ferromagnetic minerals in the rock and is extremely variable, difference in natural remanent magnetization (Nuraddeen Usman ., et al., 2017). The major application of magnetic method is for mineral exploration. In geotechnical, the Magnetic method can be used for locating underground ferromagnetic, pipelines and mapping archeological sites.

VI. GRAVITY METHOD

Gravity method is based on the measurement of variation in the gravity field caused by horizontal variation of density within the subsurface. Gravity and magnetics seek anomalies caused by changes in physical properties of subsurface rock. Also, both require fundamentally similar interpretation methods.

Gravity prospecting produces two anomalies such as negative anomalies in less dense rock such as in sedimentary basins, batholiths, subduction zones, oceanic ridges and positive anomalies in more dense rock such as ultramafic masses, uplifts of denser rock in structures such as anticlines or reverse faults (N Ismail ., et al., 2018). The major application of gravity method is for mineral exploration in combination with magnetic method. In geotechnical, gravity method used for determining in-situ rock densities and volume of organic material in filled in lakes or karsted features.

VII. WELL LOGGING METHOD

Well logging methods are important in engineering site investigation as they permit both detailed qualitative and quantitative evolution of many formation parameter. It records physical properties like caliper, density, resistivity, self-potential, natural gamma ray, neutron and sonic. With these logs lithological interpretation and correlation between boreholes to borehole is possible. In cased hole the number and type of logs is restricted. The well logging method gives 1D borehole wall surficial information. These well logging methods are popular in oil, gas and mineral explorations.

VIII. SUMMARY

Several geophysical methods are available to study the sub-surface ground conditions and to locate the buried objects or geological defects. Each method has its own advantages and limitations. The methods can be adopted within the specified range or natural ground conditions. These methods can be integrated to arrive at definite conclusions. In general, the methods give qualitative assessment of ground conditions which can be confirmed through drilling, pits or trenches. The geophysical methods can be used to optimize the trial pits, trenches, drifts and drill holes. Correlation of velocities or resistivity or electromagnetic potential with engineering properties of natural materials proposed by various researchers should be used with caution as these give only rough idea and gives a range of values. These may not address the variability in ground conditions. These methods can be employed in site specific problems. In civil engineering projects and in particular water resources projects involving large sized structures these methods can be employed during pre-feasibility stage for qualitative assessment of ground conditions for selection suitable sites. In detailed design and construction stage, these methods can be used to obtain high resolution data for and during post construction stage, it can be used for health assessment and efficacy of repair works.

Success of geophysical application lies in the physical property contrast between two materials. It may be difficult to characterize the materials with one geophysical method in complex problems due to less variation in properties. Two integrated methods can be adopted in solving complex geotechnical problems.

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