Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Significance of Acoustic and Electrical Logging Studies at Nuclear Power Plants

Govind. A. Panvalkar [1]   Amol. D. Chunade [2]

[1] Scientist 'B', Central Water and Power Research Station, Pune – 411 024, India
[2] Assistant Research Officer, Central Water and Power Research Station, Pune – 411 024, India
govindpanvalkar@gmail.com

Abstract Extensive Geotechnical investigations are carried out for designing crucial structures of a Nuclear Power Plant (NPP). As these structures enforce heavy loads on the foundation, it is imperative to evaluate the properties of subsurface rocks up to sufficient depth to ensure the plant's safety. A primary requirement for design of nuclear power plants is they withstand dynamic loads up to a predefined intensity of ground motion, without endang ering their safety. The properties of foundation materials are therefore of paramount importance as they can affect the structural safety. It is here, where in addition to surface geophysical techniques, electrical and acoustic borehole geophysical logging techniques play a major role in assessing the suitability of foundation. The subsurface parameters evaluated from these studies include electrical resistivity, primary and shear wave velocities, and dynamic moduli of elasticity which form the basis of deriving the input design values for the structure. Additionally, these methods also determine the location of weak zones. This paper highlights the importance of borehole geophysical logging in assessing the foundation for NPP with two CWPRS case studies where suitability of foundation critical structures was determined.

Keywords: Acoustic Logging, Electrical Resistivity Logging, Geophysical logging, Nuclear Power Plant.

1 Introduction

The site evaluation of a Nuclear Power Plant (NPP) entails the consideration of different factors relating to the physical and environmental aspects, as well as the compliance with many regulations and regulatory bodies. The construction phase of a new nuclear power plant is crucial to the safe operation of the facility through its design life. Geotechnical investigations are essential for site characterization that affects the design, performance and safety of NPP. These investigations also provide information required to define the local foundation and groundwater conditions as well as the geotechnical parameters needed for engineering analysis and design of foundations. Further, the geological investigations provide the required information for a better understanding of the subsurface conditions and for identifying potential geologic and earthquake hazards that may exist at site. The purpose of the foundation is to provide a stable base for the superstructure and to safely transfer all loads and their effects to the ground. The foundations of critical structures like reactor and turbine buildings must therefore be designed to ensure stability under the combined effect of static and dynamic loads. Hence, extensive and mandatory investigations of the subsurface conditions at a NPP site are important for foundation evaluation as these investigations provide information on the nature and suitability of rock foundations [1]. A combination of geotechnical and geophysical site investigations along with geological mapping (pre and post excavation) provide all information regarding the design parameters for the structure [2].

2 Geotechnical Investigations

The geotechnical investigations include direct exploration methods that are used to find information from samples, direct observations and in-situ tests. In order to comprehend the different types of soil and rocks, these methods generally necessitate drilling with extraction of cores and excavation of trenches for observation, testing and laboratory investigations on the collected samples of rocks and soil as well. The non linear behavior of soil under stress, the complexity in estimating properties of the soil in an undisturbed condition and large amount of heterogeneity and spatial variability make it unfeasible to predict the exact behavior of soil in time and space. Different approaches are used to measure the in-situ geo-technical soil properties. These include direct probing using static or dynamic penetration Techniques and or boreholes [3]. The drilling depths of the boreholes differ with the site conditions, geometric parameters of the proposed foundations and are drilled up to depth required to completely assess the site conditions affecting the structures. The minimum depth (d_{min}) of drilling is normally taken as the depth at which the change in vertical stress during or after construction for the combined foundation loading is less than ten percent of the in-situ effective overburden stress [4].

3 Borehole Geophysical Logging

Borehole geophysical logging provides an efficient and cost-effective means to obtain sub-surface information continuously with depth. These methods are nondestructive and provide information of subsurface like lithology, quality of foundation rock, bulk density, stratification, fractures, porosities etc. The various types of logs which are important in foundation studies are (i) Electrical resistivity logging, (ii) Acoustic/ sonic Logging and (iii) Nuclear logging and (iv) Caliper Logging. Borehole geophysical logging are required to study and evaluate the properties of the underlying rocks up to a depth sufficient to study and evaluate the properties of the underlying and supporting soil/rock material up to beyond which the properties can no longer affect the safety of the plant.

3.1 Electrical Resistivity Logging

Electric Resistivity logging encompasses logs in which a record of potential differences in electric current is measured. The electrical logging technique is based on the measurement of the electrical resistance or resistivity of the earth (i.e Ohm's law). Electrical logging tools commonly measure (i) the naturally occurring spontaneous potential (SP) produced by the borehole mud at the boundaries of the permeable beds (ii) the apparent resistivity of the rock formation using different types configuration viz. single-point resistance log (i.e. single point method), multiple electrode logs i.e. 16" (short-normal) and 64" (long normal) and iii) 18'8" (lateral log) with an estimation of the true formation resistivity[5][6]. E-Log is generally used to identify lithology and correlate stratigraphy. The resistivity data can be quantitatively, used to calculate water quality, hydraulic conductivity and porosity. Resistance logs are used primarily for lithologic determination, correlation and identification of fracture and washout zones [5][6].

Single-point resistance log measures resistance between a single electrode placed in a borehole and another electrode at the ground surface. Multiple electrode logs like short-and long-normal, and lateral provide better resolution of resistivity and associated properties of individual strata within the subsurface than what can be achieved with the single-point array. The 16" (short-normal) and the 64" (long normal) are records of apparent resistivity of the formations adjacent to and electrically conductive fluid filled borehole. The 18'8" later long provides and estimation of the true formation resistivity [5]. Calibration of electric logs is carried out by attaching known resistances to the electrodes in the laboratory.

3.2 Acoustic/ Sonic Logging

Acoustic or sonic logging includes techniques that use a transducer to transmit a sonic wave through the fluids in a borehole and the surrounding rock. The compressional (Vp) and shear (Vs) wave velocity of the formation adjacent to the borehole measured can provide information on porosity, lithology, and the dynamic elastic properties. The properties of foundation material are of significance because the potential effects of vibratory motions have to be considered while designing the foundations of critical structures of NPP like nuclear reactors, turbines, cooling towers and other important civil structures. The transmission of vibratory motion may lead to stress levels exceeding the design limits of the structures. The transmission of vibratory motion due to an earthquake is governed by the dynamic elastic moduli of the subsurface strata. These elastic moduli with depth are computed from compressional and shear wave velocities obtained from Full Waveform Sonic Logging. Acoustic logging is carried out in water filled borehole for a good acoustic coupling between the transmitter-receiver and the material surrounding the borehole. The method involves the generation of a very high-frequency sound wave (approx. 23 KHz) by transmitter into the formation and detection of a complex signal passing through the formation by detector. The slowness (reciprocal of the velocity), reported by the sonde, helps to calculate V_p and V_s of the formation. The mechanical properties namely Poisson's ratio (σ), dynamic modulus of elasticity (E_d) and Shear modulus (G_d) are computed from V_p, V_s and density (ρ) using the following equations:

$$\sigma = (0.5\, Vp^2 - V_s^2) / (Vp^2 - V_s^2) \qquad (1)$$

$$E_d = V_p^2 (1+ \sigma) (1 - 2 \sigma) / (1 - \sigma) \quad (2)$$

$$G_d = \rho V_s^2 \quad (3)$$

4 Instrumentation and Calibration

The Robertson Geologging™ borehole logging unit consists of (i) the probe or sonde, (ii) 200 m cable and winch, and (iii) surface data acquisition system (micro logger) for signal processing and recording. The output electronic signal of the probes is transmitted to the surface instruments via cable and winch to the surface unit (micro logger) and a recording unit such as laptop. The Winlogger™ software designed for data acquisition was used and subsequently, the data was processed suing the Viewlog™ software. The electric probe is generally calibrated using a standard resistance kit before carrying out the studies. The primary response of the electric sonde was transformed to be read as rersistivity in ohm-m using the calibration file provided with Winlogger™ software. Similarly, the log of transmitter-receiver times along with the slowness which is the primary response of the acoustic sonde was transformed to be read as microseconds per foot using the calibration file. Ideally, boreholes for operation of all logs are generally NX size i.e., of diameter 76 mm. The depth of the boreholes should be extended to 50 m or to the greatest depth for the detection of subsurface properties like the discontinuities or weakness or alteration zones [1][2].

The fundamental problem in the application of geophysical logs is that the interpretation of many logs is more of an art than science. The numerous environmental factors causing log response are difficult to analyses quantitatively. Hence various factors are considered while interpreting log data. Geophysical borehole logging is routinely applied for assessing the nature of foundation of NPP in spite of some limitations of the method. Typical case studies are presented where borehole logging has played significant role in deciding the foundation of the nuclear power plant.

5 Case Studies

5.1 Electrical and Acoustic logging at Rajasthan Atomic Power Project (RAPP), Rajasthan, India

Nuclear Power Corporation of India Ltd. (NPCIL) undertook the construction of two additional units, Units 7 & 8 at RAPP, Rajasthan, India, to generate 700 MWe of power each. RAPP is located about 60 km south west in Kota at Rawatbhata. The assessment of the variation of electrical resistivity of geological formations with depth and also the dynamic properties of rock was required for the foundation of the Reactor Building (RB) and Turbine Building (TB) for Units 7 & 8. Fig. 1 shows lay out plan of RAPP and location of boreholes for conducting electrical and acoustic logging.

Geologically, the area is primarily covered with thick-bedded, openly folded sedimentary rocks of Vindhyan Super Group comprising of Kaimur sandstone (Chittorgarh sandstone, 65 m thick), a thin soil cap above it and a localized thin shale layer in most of the surveyed area. The rock has a fine to medium grained texture.

Electrical resistivity and acoustic logging was carried out in the water filled boreholes from 15 m to 85 m depths and from 15 m to 82 m depths respectively at Reactor Building (RB-7 & RB-8) site and electrical resistivity logging from 15 m to 50 m depths at Turbine Building (TB-7 & TB-8) site below the casing. A typical electrical and acoustic log of borehole RB7 is shown in Fig. 2. The interpretation of the electrical resistivity logs indicated that in general, the resistivity of rock formation varied from 200 Ohm-m to 1900 Ohm-m. The resistivity values ranging between 200 Ohm-m and 1000 Ohm-m indicated the presence of ferruginous sandy siltstone. High resistivity values above 1000 Ohm-m indicated the presence of quartzite sandstone. A low resistivity zone was identified between depths of 42 m and 69 m in both boreholes RB-7 and RB-8 and was attributed to the presence of ferruginous siltstone.

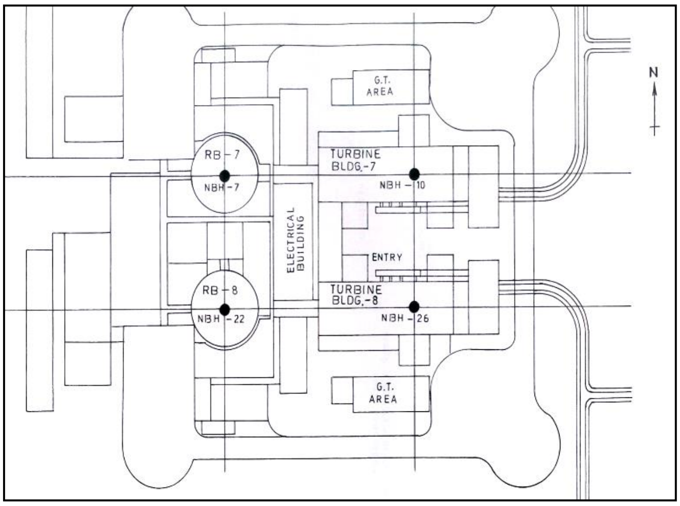
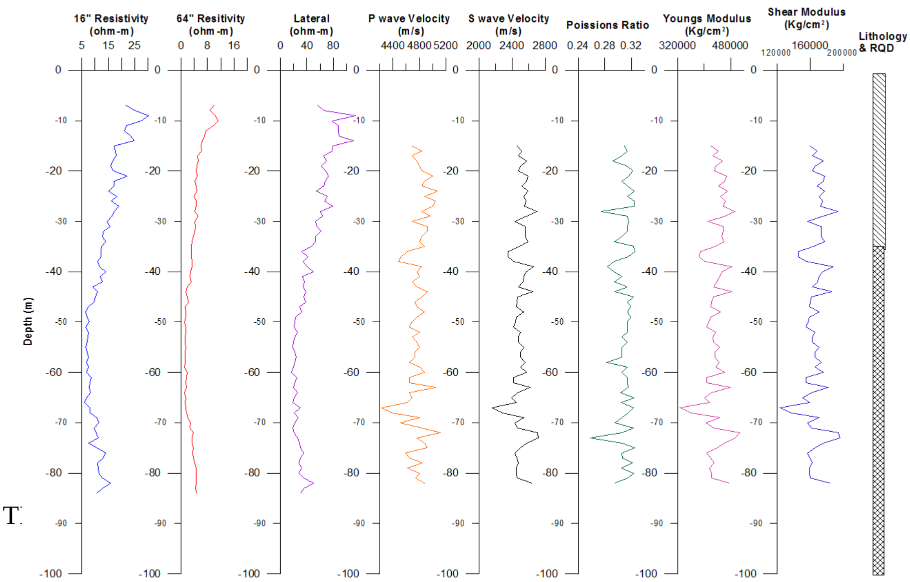


Fig: 1 Lay out plan of RAPP units 7&8, showing locations of boreholes for Electrical resistivity and Sonic Logging



T

Fig. 2 Typical Electrical Resistivity & Acoustic Logging at borehole RB-7, RAPP

The results of sonic logging carried out at RB-7 and RB-8 indicated that the primary wave velocity V_P of rock varied from 4390 m/sec to 5080 m/sec and between 4620 m/sec and 5120 m/sec respectively. The shear wave (V_s) velocity ranged between 2160 m/sec and 2720 m/sec in borehole RB-7 and ranged between 2400 m/sec and 2600 m/sec in RB-8.The density values of 2.60 g/cm^3 for RB–7 and 2.63 g/cm^3 for RB-8 was taken for computation of dynamic modulus of elasticity and shear modulus were provided by project authorities based on laboratory tests at different depths. The calculated Poisson's ratio ranged from 0.28 to 0.32 and the RQD value indicated about 60-93% recovery at RB-7 and 40-88% at RB-8. The results of electrical and acoustic logging are summarized and listed in Table-1.

Table – 1: Results of Electrical resistivity Logging and Acoustic Logging at RAPP

Zone below Ground Level (m)	Nature of foundation	Resistivity (ohm-m)	V_P(m/sec)	V_s (m/sec)	Poisson's Ratio	Ed X 10^5 (Kg/cm^2)	Gd X 10^5 (Kg/cm^2)
15-32	Quartz Arenite	780-1040	4690-5080	2430-2580	0.27-0.32	4.17-4.75	1.58-1.95
32-42	Ferrugenous silt stone	550-730	4480-4920	2350-2660	0.29-0.33	3.88-4.86	1.48-1.89
42-69	Ferrugenous silt stone	220-380	4230-5040	2160-2650	0.28-0.32	3.28-4.83	1.24-1.86
69-85	Ferrugenous silt stone	530-960	4510-5120	2430-2720	0.26-0.32	4.06-5.09	1.57-1.96

Electrical resistivity at RAPP along with acoustic logging revealed that rock (siltstone and sandstone) encountered in the boreholes was in general sound and layered. The top layer (15-32m) contained hard Quartz Arenite with high resistivity (780-1040 ohm-m) and Vp (4620-5120 m/sec) values followed by siltstone at both RB-7 & RB-8 locations. The resistivity and sonic velocity values did not indicate the presence of any remarkable fractures or weathered zones at the site. Based on the studies conducted, the foundation was considered suitable for constructing critical structures of NPP on the basis of dynamic properties of rock mass determined.

5.2 Electrical and Acoustic logging at Kakrapar Atomic Power Project (KAPP), Gujarat, India

Nuclear Power Corporation of India Ltd. envisages construction of Kakrapar Atomic power Project (KAPP) located about 70 km west of Surat in Gujarat State. The generating capacity of the power plant was to be increased by 1400 MWe by means of installing two additional nuclear reactors Units 3 & 4 with a generating capacity of 700 MWe each. Geologically, KAPP is situated on Deccan traps of Cretaceous age. The host rock at site is hard grayish basalt underlying overburden comprising back filled soil, silty clay and weathered rock. Groundwater occurs at a depth of 3 m to 6 m below the ground surface. Electrical Resistivity and Acoustic logging were conducted in boreholes drilled in the area - two at the Reactor Building site (RB-3 & RB-4) and two at Turbine Building site (TB-3 & TB-4) with depths varying between 12 m to 95 m depths and 12 m to 42 m depths respectively to determine electrical resistivity of the subsurface formations and the dynamic properties of rock respectively for designing the foundation of Reactor and Turbine Building sites of units 3 & 4 (Fig. 3).

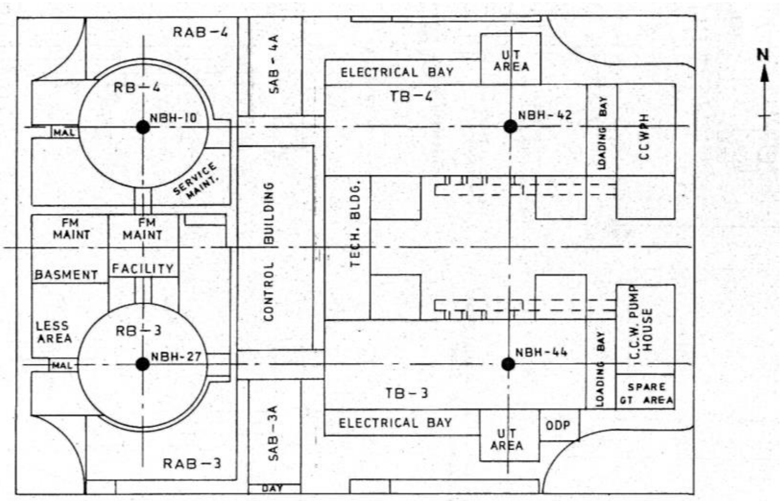


Fig: 3 Lay out plan of KAPP units 3 & 4, showing locations of boreholes for Electrical resistivity and Sonic Logging

The results of Electrical resistivity logging showed that in general, the resistivity of rock formation, varied from 70 Ohm-m to 3080 Ohm-m [7]. Theoretically, the electrical resistivity of basalt has a wide range from 10 to 10^6 ohm-m [8]. The studies revealed presence of slightly weathered basalt at depths ranging from 12 m – 42 m underlain by compact sound basalt with intermittent slightly weathered basalt zones.

The V_P and V_s of sub-surface formation, obtained from acoustic logging, varied from 4010 m/sec to 6060 m/sec and 2270 m/sec to 3180 m/sec respectively for bore hole RB-3 and between 4140 m/sec to 6160 m/sec and 2395 m/sec to 3230 m/sec respectively for bore-hole RB-4 at the Reactor Building site. The mechanical properties like Poisson's Ratio, Young's and Shear modulus of elasticity, were computed using density value of 2.8 g/cm^3 obtained from the rock core samples in the laboratory. The comparison of electric and sonic log at RB-3 showed a fractured zone at a depth of 80 m - 87 m having a low resistivity. But the compactness of lithology was confirmed by the continuous monotonic high values of V_P and V_s along with little variation at some depths.

Fig. 4 shows a typical combined electrical resistivity and acoustic logging plot at RB-3. The results of electrical and acoustic logging are summarized in Table-2.

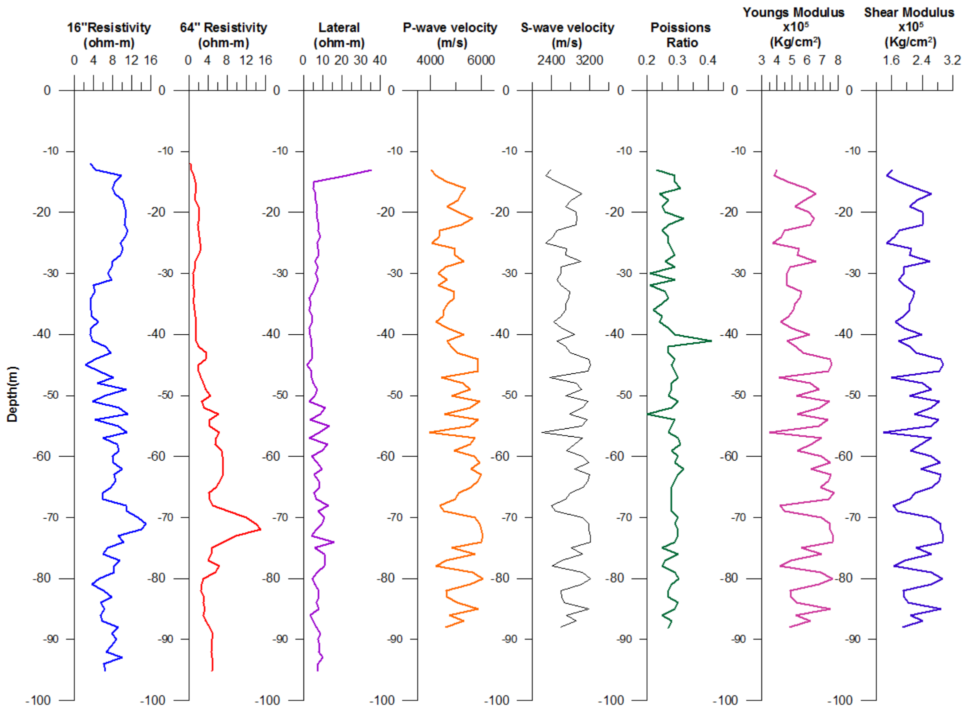


Fig. 4 Typical Electrical Resistivity and Acoustic Logging at borehole RB-3, KAPP

Table – 2: Results of Electrical resistivity Logging and Acoustic Logging at KAPP

Zone below Ground Level (m)	Nature of foundation	Resistivity (ohm-m)	V_p(m/sec)	V_s (m/sec)	Poisson's Ratio	Ed X 10^5 (Kg/cm^2)	Gd X 10^5 (Kg/cm^2)
12 – 42	Slightly weathered Basalt	100 – 240	4010 - 5644	2271-3037	0.23-0.32	3.74-6.56	1.47-2.64
42 – 65	Slightly weathered Basalt	200 – 730	4417 - 5976	2200-3213	0.27-0.32	4.14-7.58	1.38-2.95
65 – 80	Sound basalt	400 – 1200	4204 - 6058	2398-3216	0.25-0.30	4.19-7.71	1.64-2.96
80 – 87	Slightly weathered Basalt	250 – 360	4618 - 6036	2592-3205	0.27-0.30	4.88-7.65	1.92-2.93

6 Conclusion

Geotechnical and geophysical investigations are beneficial to evaluate the suitability of foundation for a Nuclear Power Plant for its safety. Among these investigations, geophysical investigations have provided optimum and economically feasible solutions to assess all the pertinent rock characteristics. As boreholes are one of the most effective means of obtaining detailed information on geologic formations in the subsurface and their engineering properties, geophysical logging provides significant parameters for assessing the foundation. Integration of different logging techniques are highly beneficial as multiple parameters obtained provide an enhanced data correlation. Although a single log response may be dominant in a given area, correlations derived by considering all the different log responses as a composite group present a superior sub-surface characterization. Although major correlations are usually based upon subtle differences in the physical properties of the penetrated sub-surface, these high-resolution logging procedures provide an added advantage. The measurements of sub-surface electrical resistivity, compressional and shear wave velocities are most commonly used for considering the suitability of the foundation. On the basis of assessment of nature of foundation by borehole logging from the evaluated dynamic properties of the rock and the high RQD Values obtained, it was inferred that the foundations at both Atomic Power Projects were considered suitable for the construction of the Reactor and Turbine Buildings of Nuclear Power Plant. The application of these techniques has thus proved their potential to decide upon the foundation of critical structures of a NPP.

7 Acknowledgement

The authors are grateful to Director, CWPRS, Pune for his guidance, encouragement and permission to publish this paper. The authors are obliged to the motivation and valuable guidance by Dr. Prabhat Chandra, Additional Director and Shri B. Suresh Kumar, scientist-D. The authors are also indebted to all the retired officers for their valuable contribution at the time of conducting the studies. Facilities and co-operation provided by the authorities of Kakrapar Atomic Power Project (KAPP), Gujarat and Rajasthan Atomic Power Project (RAPP), Rajasthan, India are acknowledged with thanks.

References

1. INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA) (2004), Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants , NS-G-3.6.
2. Boominathan A (2004) Seismic site characterization for nuclear structures and power Plants, Current Science, 87 (10), 1388-1397.
3. O. J. Akintorinwa* and J. I. Adesoji, Application of geophysical and geotechnical investigations in engineering site evaluation, International Journal of Physical Sciences Vol.4 (8), pp. 443-454, August 2009.
4. P. Ravi*, G. Visalkshi*, G. Prabhakar*, D. K. Jain#, R. P. Garg#, U. S.P. Verman, NPCIL, Mumbai Significance of Geo-Technical And Geophysical Investigations for

a Nuclear power Plant site CONFERENCE on Geotechnical Engineering Experiences and Practices, New Delhi May 2007.

5. Keys, WS (1990) Borehole geophysics applied to water-resources investigations: U.S. Geological Survey Techniques of Water Resources Investigations, book 2, E2, 150.
6. Benson RC (1991) Remote Sensing and geophysical methods for evaluation of subsurface conditions. In: David MN (editor), Practical Handbook of Groundwater Monitoring, Lewis Publishers Inc., Chelsea, Michigan, 143-194.
7. R. K Kamble, CK Rani, N. Ghosh and G. A. Panvalkar Acoustic and electrical logging for evaluation of resistivity and shear and compressional wave velocities of foundation of Kakrapar nuclear power plant, Jpournal of Geopbhysics vol. 33, No4, October 2012
8. Telford W M, Geldart L T, Sheriff R E & Keys D D (1976) Applied Geophysics, Cambridge University Press, PP 450-454.