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Importance of Borehole Logging Studies in Design of Foundation for Civil Engineering Structures

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Abstract Design of foundation, an important role for any major civil engineering structures viz. Nuclear and Thermal Power Plants, bridges, dams, barrages etc., involves geotechnical investigations for determining detailed subsurface information; site characterization and damping characteristics of soil/ rock etc. Borehole geophysical logging, compliment and supplement to geotechnical investigations, provide in-situ properties of subsurface lithology in a rapid, non destructive and cost effective way. Purpose of the paper is to highlight importance of borehole logging like nuclear, sonic and electrical logs in foundation studies for determining in-situ density, compressional wave velocities (Vp), shear wave velocities (Vs) and sub-surface resistivity for identifying depth and quality of bed rock, different subsurface layers or strata, presence of liquefaction zone, Low Velocity Layer (LVL) and structural discrepancy i.e. cracks, fracture and fault zone/ shear zone etc. and also calculating dynamic elastic properties of subsurface lithology, important for design-foundation of important civil structures. This paperis enlightened with different case studies where CW&PRS, Pune was deeply involved in design-foundation of important civil structures like Nuclear and Thermal Power Plants, jetties etc. by providing subsurface geophysical and geotechnical information using land and underwater borehole logging. Discussion on importance of borehole geophysical logging in foundation studies in this paper may be useful to geotechnical engineers and professionals dealing with design-foundation of important civil structures.

Key words: Foundation studies; design foundation; foundation rock; subsurface lithology; borehole logging

1 Introduction

Engineering properties and deformational characteristics of rock mass plays a vital role in design of foundation of important civil structure like Nuclear Power Plant, Thermal Power Plant, dam, bridge etc. (IAEA Safety Guide, 2004). The physical and engineering properties of subsurface strata provide useful information regarding ground motion behaviour, natural frequencies, material damping characteristics, design parameters etc. A comprehensive data on soil properties including strength and consolidation parameters, often required prior to the design of foundation, are bulk density, moisture content, porosity, void ratio etc. of subsurface soil and also maximum stiffness (G_{max}) of soil at very low strain ($< 10^{-3}$ %), in general. Assessment of the subsurface lithology i.e. nature and quality of lithology, correlation of subsurface strata, depth and thickness of the formations, presence of structural discrepancy, if any, porosity, liquefaction potential, anisotropy, low velocity layers, voids or anomalies within geological layers, weathering of the foundation rock (Keys, 1971) etc. are important for design of foundation. In situ values of the elastic moduli, densities and other geotechnical parameters are mandatory to verify the suitability of rock foundations for the determination of soil-structure interaction, natural frequency of the reactor-foundation rock system (IAEA Safety Guide 2004), load bearing capacity of the foundation (Bahremandi et al 2012) and also design of earthquake resistant structures, as well.

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. Non-destructive geophysical borehole logging viz. nuclear logging (i.e. natural gamma log, gamma-gamma density log and neutron-neutron log), electrical logging and sonic or acoustic logging etc. provide physical properties of earth or in-situ geophysical parameters i.e. density, resistivity, seismic velocities etc. in continuous fashion as a function of depth by means of lowering sensor (sonde or probe) in NX size (dia. 76 mm) borehole and recording at the surface (Key, 1971). Borehole logging techniques are rapid, cost effective with better depth resolution and also be repeated over a period of time, if necessary.

Objective of this paper is to highlight importance of borehole logging for providing subsurface information regarding nature and quality of soil and or rock competence for design of foundation of major civil engineering structures and dredging of channel, as well with the help of different case studies where CW&PRS, Pune was deeply involved.

2 Borehole logging technique

Nuclear logs are based on measurement of either natural radiation of radioactive elements i.e, potassium (^{40}K), thorium (^{232}Th) and uranium (^{238}U) within the formation using *natural gamma log* for identification of lithology and stratigraphic correlation etc. or transient response of artificial radioactive sources i.e. Caesium-137 (^{137}Cs) or Cobalt-60 (^{60}Co) and Americium-241-Beryllium, kept in the probe using *gamma- gamma density log* and *neutron-neutron log*, respectively for the measurement of bulk density of rock, porosity of the formation, moisture content and identify lithology etc. (Key, 1971).

Detector of gamma-gamma density log detects the attenuation of back scattered gamma rays, injected from artificial sources (^{137}Cs or ^{60}Co), after collision with electrons of minerals in terms of CPS (counts per sec.). Detector of the neutron-neutron log detects returned neutrons (slow or thermal neutron), emitted from artificial source i.e. Americium-241-Beryllium into the formation, after encountering collision with hydrogen atoms in terms of CPS.

The variation of the potential, directly proportional to the resistivity of the formation on the basis of Ohm’s law, the current emitted from and potential difference obtained from the resistivity sonde (or probe) of the *electrical log* provides information about the apparent resistivity of the material surrounding the electrodes. Resistivity logs are used in correlating the lithology with the help of variation of electrical resistivity of geological formations, both laterally and vertically, identifying pore fluid, formation resistivity, hydrological parameters etc (Key, 1971).

Acoustic logging use medium to high-frequency (5 – 20 KHz) acoustic (sonic) energy emitted from probe or sonde to obtain seismic velocities i.e.

compressional and shear wave velocities (Vp and Vs) of the formations of the geologic material around the borehole (Key, 1971).

Dry or water filled, vertical borehole of NX size (dia. 76 mm) with PVC casing from top to bottom is required for nuclear logging, whereas water filled of same type of NX sized borehole without casing is required for electrical and acoustic or sonic logging. A combination of acoustic or sonic logging, gamma-gamma density log and neutron-neutron logs provide detailed information of lithology and more accurate estimates of porosity, though none of these logs measure porosity directly. The interpretation of density w.r.t depth of subsurface lithology is done by calibrating log data i.e. CPS (counts per second) w.r.t depth with the density calculated in laboratory using core samples from selective depth. The interpretation of rock type is done by comparing log data (i.e. resistivity and acoustic velocity vs. depth) with lithologs.

3 Importance of Borehole logging studies in design of foundation

3.1 Identification of geotechnical parameters of subsurface lithology and soil properties

Geotechnical parameters are clay coefficient or shaliness, bulk density, bulk moisture content, specific gravity (i.e. ratio of mass of soil to mass of equal vol. of water) and other engineering parameters viz. dry density (i.e. ratio of weight or mass of dry soil to total vol. of soil), natural moisture content (i.e. ratio of mass of water to mass of solids), porosity (i.e. ratio of vol. of voids to total vol. of soil), void ratio (i.e. ratio of vol. of voids to vol. of solids) and moisture degree, as well. Presence of voids and moisture even fluid within soil plays a vital role in reducing strength, stiffness, bearing capacity of soil and also initiating hydraulic conductivity or permeability, liquefaction state of soil and soil deformation (Bowles 2012), as well. Bulk density, dry density, specific gravity indicates compaction of soil, shear strength, compressibility, load carrying capacity (Chik et al 2014) of soil. Porosity and void ratio, measurement of denseness (or looseness) of soils, are inversely related to the soil density.

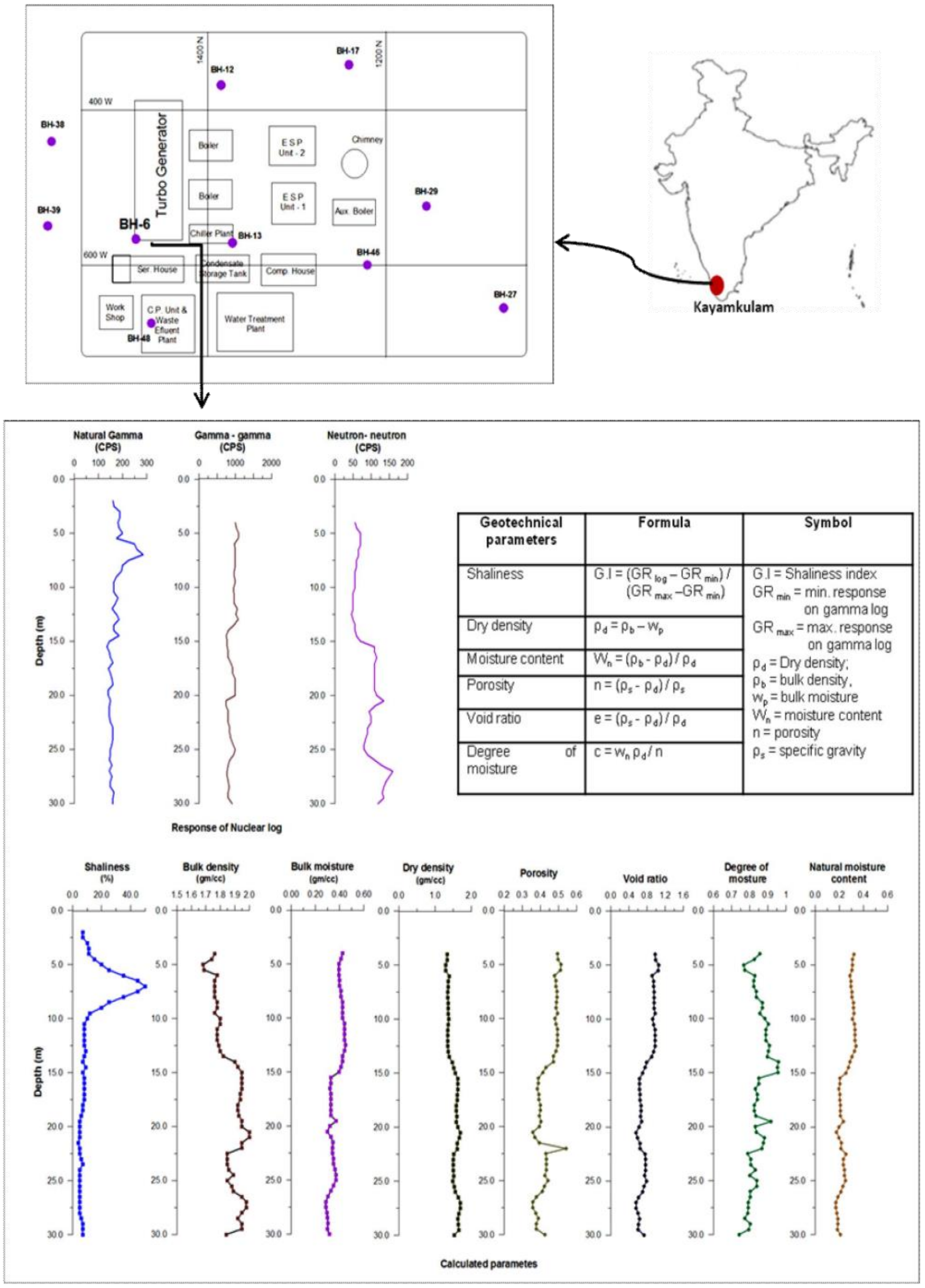
For dredging of approach channel of any port, above mentioned geotechnical properties and type of soil to be dredged i.e. silt, sand, clay and rock plays a crucial role in selection of dredging equipment, methodology, planning and deciding cost (Johnson et al 2003), as well.

Nuclear logging i.e. natural gamma, gamma-gamma and neutron-neutron log provides information regarding presence of clay, density and porosity as a function of depth and other engineering parameters are calculated using mathematical formulae (Fig. 1, 3) as well.

Kayamkulam Super Thermal Power project, Stage – I, Kerala

Geotechnical investigations were carried out at Kayamkulam Super Thermal Power project, Stage – I, Kerala prior to the construction of turbo-generator, boiler etc. at site (Kamble et. al. 1998, CW&PRS Report No.2742).

As suitable bed rock was not available upto a depth of 50 m at site after drilling at Kayamkulam site, subsurface marine deposits i.e. unconsolidated alluvium comprising of water saturated clayey and sandy soils in varying proportion with depth were considered as foundation material at site for the construction of critical structures. Marine clay is uncommon type of clay, in general and normally exists in soft consistency. Therefore,experts of the aided country Union of Soviet Socialist Republics (USSR) or Soviet Union, and M/s National Thermal Power Corporation Pvt. Ltd. (NTPC) of India, as well, suggested employing of nuclear logging at Kayamkulam site (Fig. 1) for getting bulk density, bulk moisture content and also other geotechnical properties.



Geotechnical parameters	Formula	Symbol
Shaliness	$G.I = (GR_{log} - GR_{min}) / (GR_{max} - GR_{min})$	G.I = Shaliness index GR_{min} = min. response on gamma log GR_{max} = max. response on gamma log ρ_d = Dry density; ρ_b = bulk density, w_p = bulk moisture W_n = moisture content n = porosity ρ_s = specific gravity
Dry density	$\rho_d = \rho_b - w_p$	
Moisture content	$W_n = (\rho_b - \rho_d) / \rho_d$	
Porosity	$n = (\rho_s - \rho_d) / \rho_s$	
Void ratio	$e = (\rho_s - \rho_d) / \rho_d$	
Degree of moisture	$c = w_n \rho_d / n$	

Fig. 1. Schematic diagram of site plan, response of nuclear log and geotechnical parameters as a function of depth atBH-6, Kayamkulam Super Thermal Power project, Stage - I Kerala

of subsurface deposits, prior to the design of foundation. Nuclear logging technique was conducted by CW&PRS, Pune in twelve (12 no.) of boreholes of NX-sized (dia. 76 mm) and with PVC casing at selected places at Kayamkulam site (Kamble et. al. 1998, CW&PRS Report No. 2742) upto a depth varying from 12.5 m to 35.8 m. As count rates (CPS or counts/ sec) of the detector for any formation i.e. low count rate of gamma- gamma log and high count rate of neutron-neutron log within same formation indicates high bulk density and low porosity i.e. high compactness of the formation and vice versa, Figure 1 showed low count rate of gamma- gamma log and high count rate of neutron-neutron log indicating presence of high density and low porosity marine deposits at a depth of 13.0 m – 30.0 m at borehole no. 6 (i.e. BH-6) among 12 boreholes, already mentioned above, at Turbo generator site (CW&PRS Report No. 2742). Bulk density of soils varies between 1.0gm/cc - 2.0 gm/cc (Chik et al 2014), in general. Bulk density, an indicator of soil compaction, with an increasing trend from 1.68 gm/cc to 2.0 gm/cc with depth indicated presence of either good compact soil having low porosity and less quantity of water within it or high sand content at BH-6 within marine deposit as sand content has a profound effect on soil bulk density. Specific gravity was 2.65 throughout depth indicating presence of high quantity of sand within subsurface and good soil compaction (Bowles 2012), as well. Dry density, directly related to the compaction of soil, varied between 1.30 gm/cc – 1.70 gm/cc at BH-6. The valueof the same parameter was increased after 13.0 m depth similar to the bulk density (Fig.1), indicating increase of sand quantity within medium. Other parameters viz. natural moisture content, porosity, void ratio and degree of moisture varied between 0.168 – 0.336; 0.358 – 0.541; 0.559 – 0.992 and 0.741 – 0.959 respectively at BH-6. Porosity and void ratio was reduced after 13.0 m depth indicating presence of denser soil or sandy soils at depth (Fig. 1) because higher porosity is found in clay soils than sandy soils.

From the logging data and calculated parameters at BH-6 and also from overall bulk density i.e. 1.57 gm/cc – 2.18 gm/cc and bulk moisture content i.e. 0.30 gm/cc – 0.48 gm/cc (CW&PRS Report No. 2742) at Kayamkulam site, it was revealed that unconsolidated soil was compact in nature because of presence of more quantity of sand within soil and with low porosity and moisture content, as well.

Mangalore Super Thermal Power project, Stage – I, Karnataka

Geotechnical investigations were carried out at Mangalore Super Thermal Power project, Stage – I, Karnataka prior to the construction of turbo-generator, boiler etc. at site (Kamble et. al. 1997, CW&PRS Report No. 2766).

Geotechnical site for foundation of Thermal Power project at Mangalore was covered with laterite underlain by weathered and compact granite. Laterite, considered as soft rock and having low bearing capacity and uncertain behaviour i.e. variable strength with increase of depth (Kamble et. al. 1997). At site, laterite was porous with inherent pores and permeable in nature with cavities filled with lithomargic clay whereas granite, the bedrock, suitable for foundation, was fractured, jointed and also moderate to high weathered at top and massive at depths (CW&PRS Report No. 2766). Lithomargic clay, a product of laterization and abundantly available in the western coastal belt of Southern India, is present in between weathered laterite and hard granite gneiss. Their strength is high in dry conditions, whereas soil is problematic as it loses its strength upon saturation (Naik 2016) and highly susceptible to erosion. Therefore, design of foundation for Thermal Powerproject needed subsurface information regarding density, porosity and bulk moisture of the overburden, laterite and parent rock (i.e. granite) using nuclear logging at selective places as suggested by the experts of USSR or Soviet Russia and NTPC, India, as well.

Nuclear logging technique was conducted by CW&PRS, Pune in ten (i.e. 10 no.) NX-sized boreholes (dia. 76 mm) at selected places of Thermal Power Project site (Kamble et. al. 1997, CW&PRS Report No. 2766)upto a depth varying from 12.5 m to 25.0 m for identifying geotechnical parameters viz. clay coefficient or shaliness, bulk density, bulk moisture content and other engineering parameters calculated using mathematical formula (Fig. 2).

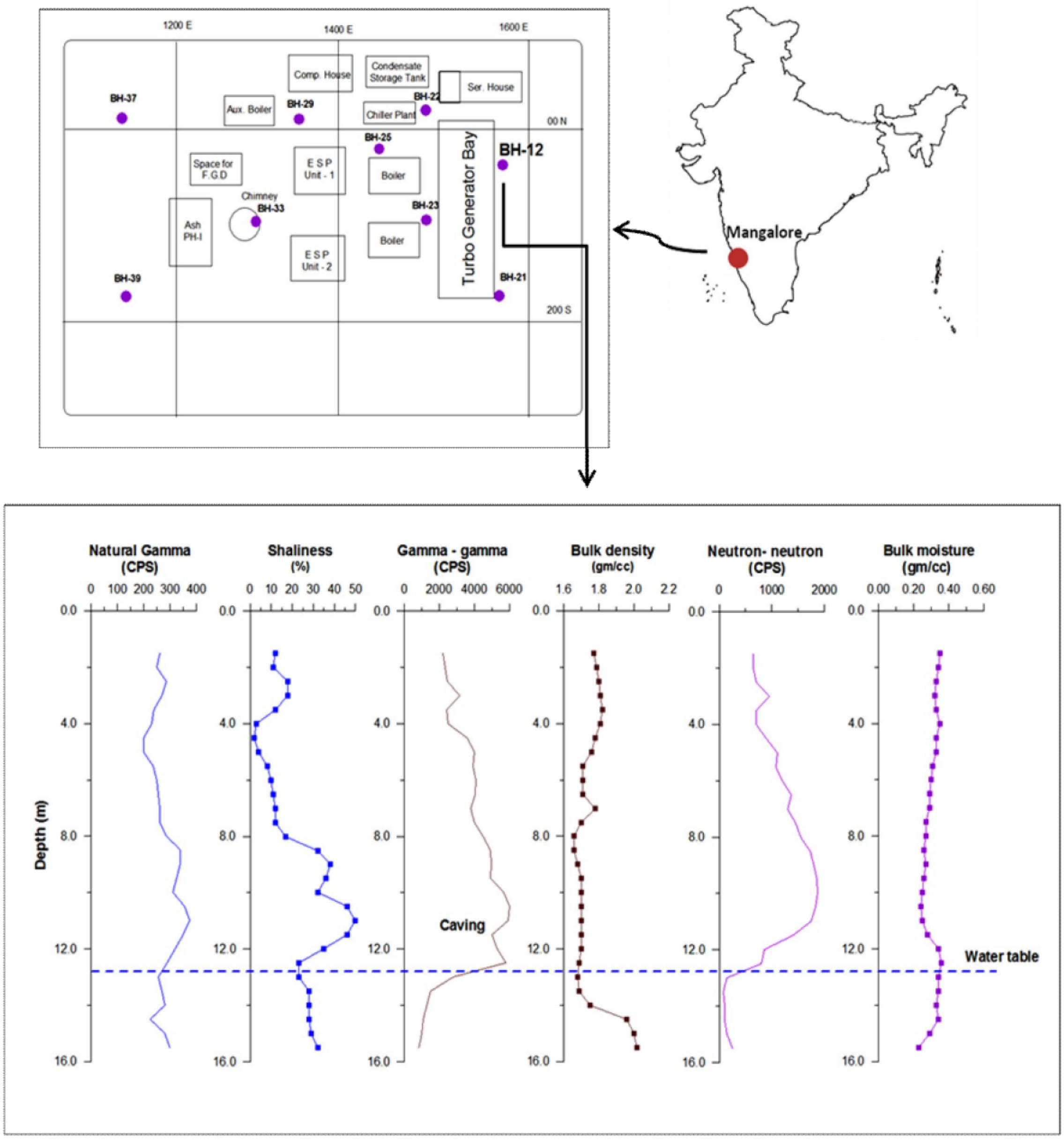


Fig. 2. Schematic diagram of site plan, response of nuclear log and geotechnical parameters as a function of depth atBH-12, Mangalore Super Thermal Power Project, Karnataka

Figure 2 showed the response of natural gamma log, gamma-gamma log and neutron-neutron log andalso derived parameters viz. shaliness, bulk density, bulk moisture content respectively as a function of depth atborehole no. 12 (i.e. BH-12) among above mentioned 10 boreholes, near to turbo generator bay at site.

Identification of subsurface cavity using geophysical anomaly depends on its size and the nature of the filling material (air, water, clay, etc.), in general. A caving was identified between 8.0 m and 12.0 m depth (approx.) by higher CPS of gamma-gamma log indicating presence of low density material (i.e. 1.66 gm/cc to 1.70 gm/cc) at that depth. The presence of low density material and gradual increase of shaliness at that depth indicated presence of clay or silt deposit within cavity. The presence of low density material in the range of 1.66 gm/cc to 1.70 gm/cc within cavity and high CPS of neutron-neutron log response at that depth indicated presence of deposited material within cavity in dry condition (Gong et al 2003) and low bulk moisture content respectively. Specific gravity varied between 2.3 to 2.7 at BH-12.

The overall bulk density of lateritic overburden and weathered bedrock (granite) at site was about 1.80 gm/cc to 2.10 gm/cc and 2.10 gm/cc to 2.40 gm/cc (CW&PRS Report No. 2766) respectively. Nuclear logging provided relevant geotechnical information viz. bulk density, porosity, moisture content etc. as a function of depth of lateritic overburden and weathered bedrock (granite) and also presence of cavity with depth.

Tuticorin port, Tamilnadu

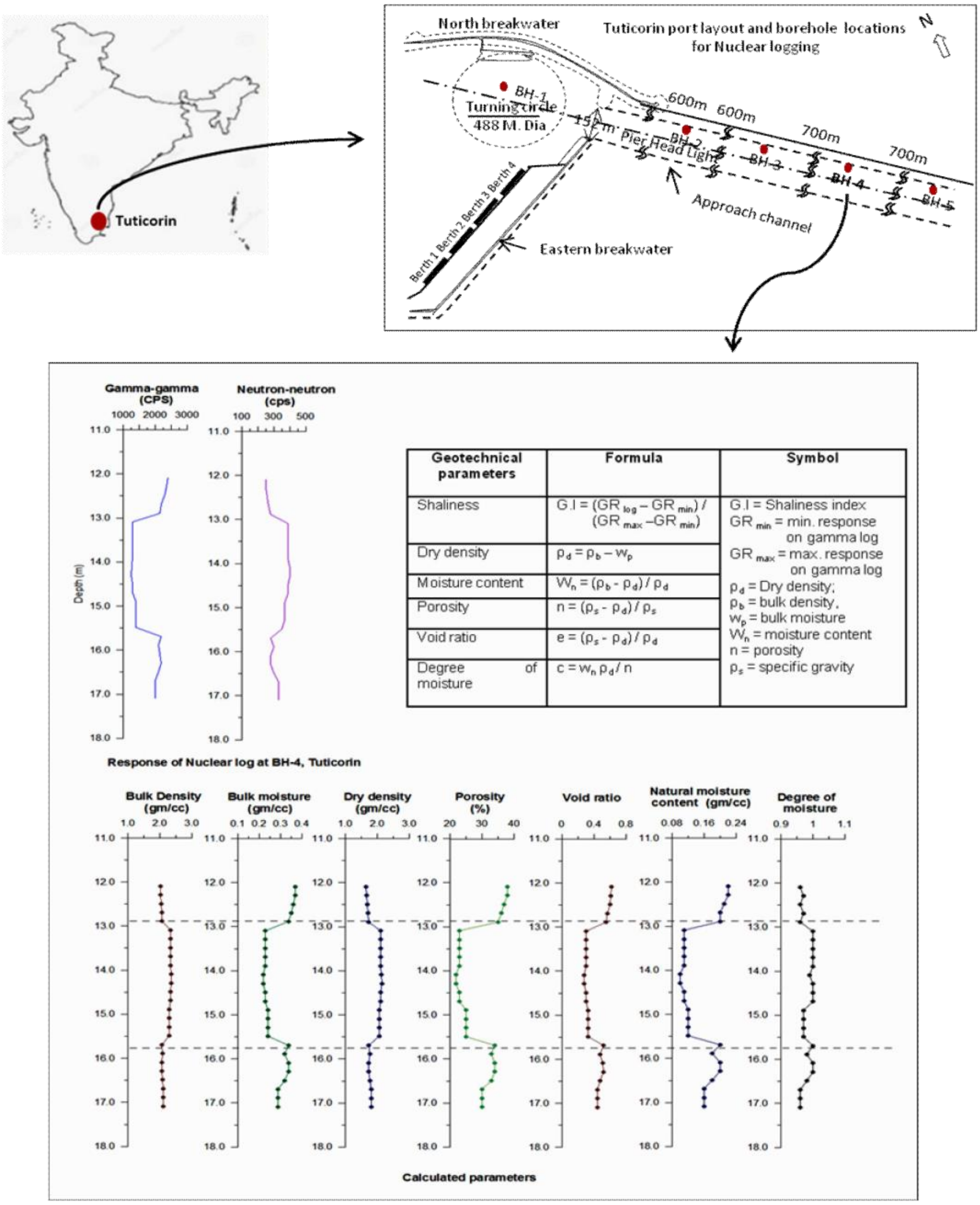
Geotechnical investigation was carried out at Tuticorin port, Tamilnadu for engineering prefeasibility studies for the construction of seventh cargo berth to cope up with huge cargo traffic. Geotechnical properties and subsurface stratigraphic information including rock levels was required for dredging of the approach channel and turning circle area (Fig.3).

Underwater nuclear logging technique was employed by CW&PRS within five boreholes (Fig.3) upto a depth of about 5.0 m below the sea bed at the approach channel and in turning circle area for identification of subsurface lithology and in-situ properties of subsoil viz. bulk density, bulk moisture, dry density, porosity and other parameters (Rani et al 1997, CW&PRS Report No: 3330).

Gamma-gamma density logging and neutron-neutron logging identified different layers, using density and porosity contrast between marine deposits (Fig.3) at borehole no. 4 (i.e. BH-4) among 5 boreholes, already mentioned above, within approach channel. Figure 3 showed the variation of bulk density, porosity and specific gravity as a function of depth was 2.02 gm/cc – 2.36 gm/cc, 22 % - 38 % and 2.61-2.73 respectively (CW&PRS Report No: 3330), indicating presence of different subsurface layers. A limestone bed with thickness 2.6 m (from depth of 12.99 m to 15.59 m) was identified on the basis of high bulk density (density of limestone ~ 2.2 - 2.7 gm/cc, Arsyad et al 2020), dry density and low value of bulk moisture content, porosity, void ratio etc. at BH-4 site. Gamma- gamma and neutron- neutron log signatures from depth 12.99 m to 15.59 m indicated presence of compact limestone without any significant structural disturbances.

After interpretation of nuclear logging data at five boreholes, five different subsurface layers i.e. silty sand, cemented sand, sand with gravel or shells or limestone pebbles, limestone and shelly limestone were identified based on bulk density and porosity at site. The overall limestone or shelly limestone of thickness 1.6

m to 2.6 m of that area showed the range of bulk density of 2.30 – 2.47 gm/cc. Information regarding subsurface layers, and relevant geotechnical parameters, indicating compaction of soils was useful in planning dredging activities of the approach channel and turning circle area in cost effective way.



Geotechnical parameters	Formula	Symbol
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Porosity	$n = (\rho_s - \rho_d) / \rho_s$	
Void ratio	$e = (\rho_s - \rho_d) / \rho_d$	
Degree of moisture	$c = w_n \rho_d / n$	

Fig. 3. Schematic diagram of site plan, response of nuclear log and geotechnical sub-soil parameters as a function ofdepth at BH-4, Tuticorin port, Tamiladu

3.2 Assessment of foundation rock

The variation of resistivity and acoustic or sonic velocities, using electrical resistivity logging and acoustic or sonic logging, provides detailed subsurface information in terms of number of layers or strata, depth and quality of bed rock i.e. weathered or compact etc. Vp and Vs is an effective parameter for determining the stiffness or bearing capacity of materials, dynamic elastic moduli under low strain level ($<=10^{-6}$) and strength of the rock (Bahremandi et al 2012) etc. Dynamic properties of rock (i.e. dynamic modulus of elasticity (E_d), Shear modulus (G_d), Poisson's ratio (σ)) are computed using Vp, Vs and density. Density is either calculated in laboratory by testing of core sample or in-situ value derived from nuclear logging at site. Interpretation of the electrical and sonic logging data is confirmed with the help of RQD (Rock Quality Designation) value w.r.t depth at site.

Kakrapar Atomic Power Project (KAPP), Gujarat

Assessment of subsurface lithology and calculation of dynamic properties of rock, as well prior to the design of foundation of Units 3 & 4 at Kakrapar Atomic Power Project (KAPP), Gujarat (Kamble et al 2012, CW&PRS Report no. 4111, 4124) under the supervision of Nuclear Power Corporation of India Limited (NPCIL) was done by CW&PRS, Pune, using acoustic and electrical logging (Fig.4). Subsurface rock was basalt of Deccan traps overlain by silty soil and weathered rock. The groundwater level is at a depth of 3 m to 6 m below the ground surface. Both acoustic and electrical logging (i.e. single point, short normal, long normal and lateral log) were carried out in two NX size (dia. 76 mm), water filled boreholes below the casings from 13 m to 88 m (Fig.4) at Reactor Building-3 (i.e. RB-3) and Reactor Building-4 (i.e. RB-4) sites.

Among Deccan basalt, moderately weathered or fractured or vesicular basalt, being porous, permeable and saturated with water and hard and compact basalt showed, in general, lower resistive zones i.e. 40 ohm-m - 70 ohm-m and higher resistive zone i.e. > 70 ohm-m, respectively (Kamble et al 2012). The result of electrical logging showed a wide variation of resistivity (80 ohm-m - 3080 ohm-m) at RB-3 & RB-4, indicating presence of compact and massive basalt around the borehole with alternating zones of semi weathered basalt (CW&PRS Report no. 4124) at certain depths (Fig.4). Acoustic logging was conducted upto a depth of 88 m at the same site for the assessment of the underlying foundation rock in terms of quality and depth. A continuous monotonic high values of Vp (4000 m/sec - 6000 m/sec) and Vs (> 2400 m/sec) with depth along with little variation at some depths (Fig. 4, 5) at RB-3 and RB-4 site indicated presence of semi weathered basalt in between compact basalt (CW&PRS Report no. 4111).

As poisson's ratio (σ) of the most consolidated rock materials, varying between $\sigma = 0.1$ and 0.33 (Bahremandi, 2012), is suitable for foundation, poisson's ratio (σ) of basaltic rock at RB-3 and RB-4, varying from 0.23 - 0.32 and 0.21 – 0.31 respectively with depth, indicated presence of good quality of rock at site and suitable for foundation of reactor building of KAPP.

A drop of resistivity value and Vp and Vs at the depth of 80 m – 87 m after an increasing trend of the same between 42 m to 80 m at RB-3 site (Fig. 4) and low value of Vp, Vs at 28 m – 36 m, 53 m – 60 m and 80m – 87 m respectively at RB-4 site (Fig. 5) might be due to the presence of narrow macroscopic fractured

(Sjogren et al 1979) zone or weathered zone within rock. Tomographic study by CWPRS at RB-4, KAPP also revealed the presence of weak zones at different depths (Wadhwa et al 2009).

The foundation rock with high seismic velocities and less structural discrepancy and high resistivity indicated presence of compact rock, suitable for the foundation (Wadhwa, 2010), supported by Poisson’s ratio, high RQD values and the dynamic properties of rock determined using Vp, Vs and density.

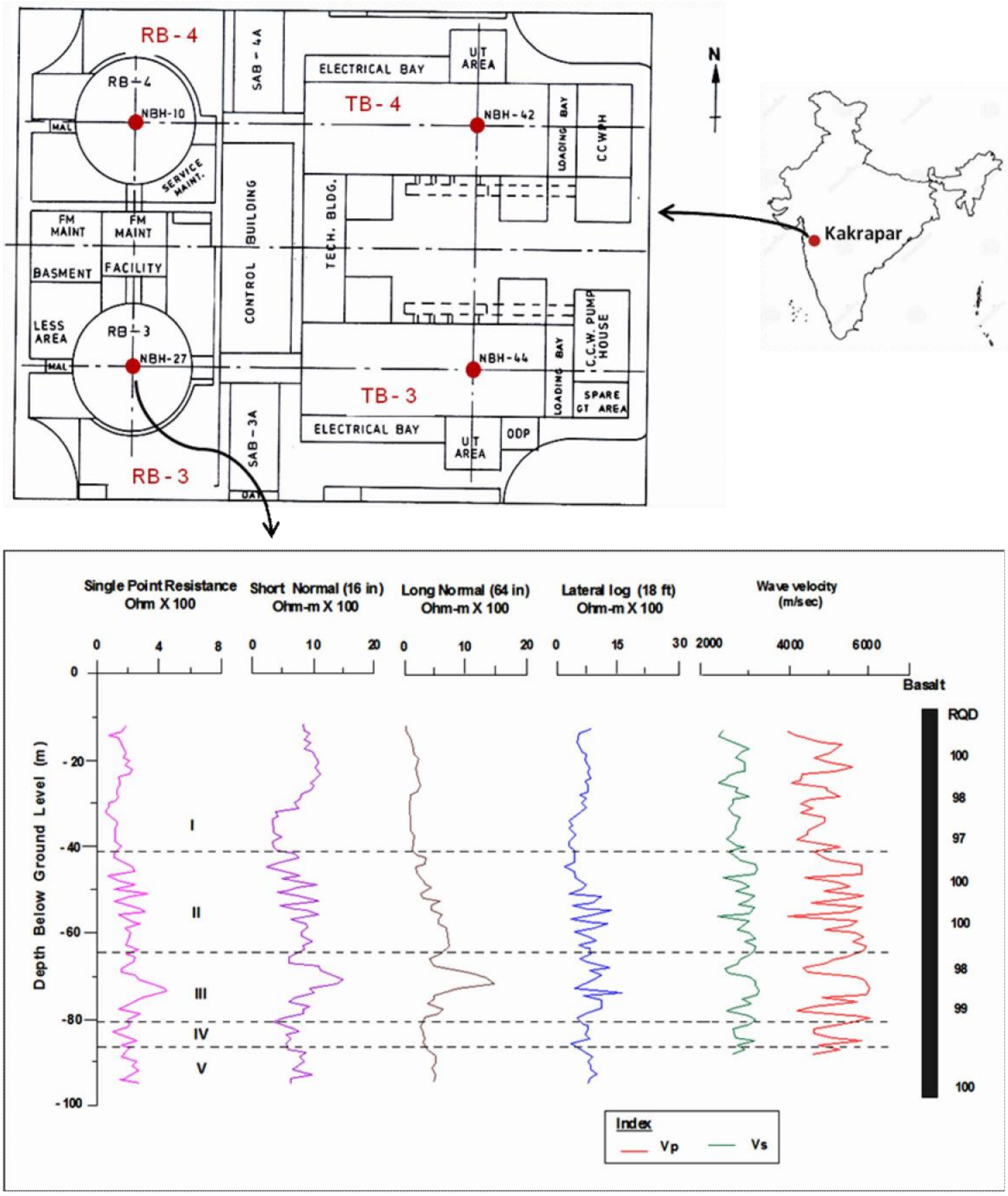

Fig. 4. Schematic diagram of site plan and electrical resistivity and acoustic or sonic logging data as a function of depth at RB-3 site, Kakrapar Atomic Power Project (KAPP), Gujarat

4 Conclusion

Nuclear logging provided geotechnical parameters viz. bulk density, porosity, bulk moisture content as a function of depth for identification of compactness of subsurface alluvium and marine deposit for design of foundation of Thermal Power project at Kayamkulam, Kerala. Subsurface condition of lateritic soil alongwith weathered and compact granite was identified by nuclear logging prior to the construction of Thermal Power project at Mangalore, Karnataka. Detailed geotechnical parameters of subsurface layers and compaction of soils, provided by nuclear logging was useful in planning dredging activities of the approach channel and turning circle area at Tuticorin port, Tamilnadu.

Electrical and acoustic logging provided subsurface information in detail regarding presence of semi weathered and massive and compact basalt without much structural disturbances, suitable for foundation of Nuclear Power Project at Kakrapar, Gujarat. The acoustic or sonic velocities helped in calculation of dynamic properties of foundation rock, important for design of foundation.

The in-situ continuous subsurface information, provided by borehole logging in rapid and sufficed with geotechnical information, was useful to geotechnical engineers and professionals dealing with design of foundation of important civil structures and dredging purpose, as well.

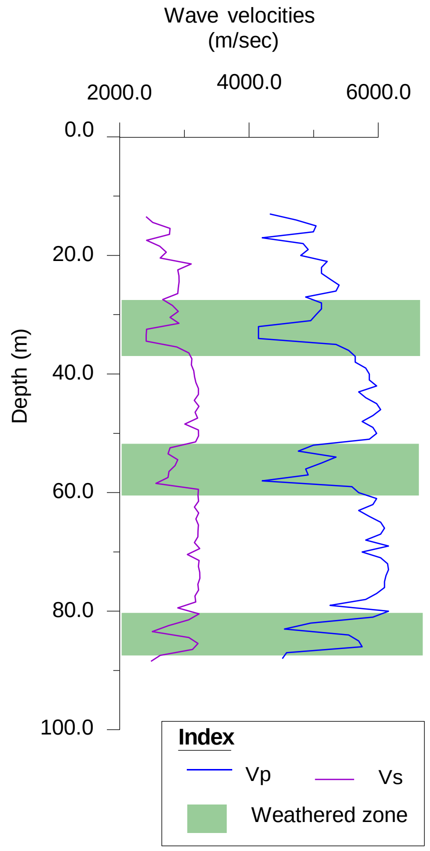

Fig. 5. Vp, Vs as a function of depth at RB-4, Kakrapar Atomic Power Project (KAPP), Gujarat

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