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Subsurface Investigation – Integrated and Modern Approach

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Abstract: Subsurface exploration is an indispensable component of any project and requires understanding of the engineering and geologic properties of the soil and rock strata and groundwater conditions that could be useful for the new design project and evaluate performance of the existing project for the retrofitting. Conventional way of drilling borehole, logging subsurface layer information with Standard penetration test N values measurement and arriving at soil properties through laboratory experiments are useful for simple project up to some extent, but may not be always effective for subsurface investigation for unusual cases. This article presents problem associated with conventional practice of surface exploration in unusual cases in a modern geotechnical world. Also explaining the integrated and modern approach adopted to estimate required properties for the design and performance assessment by using advanced subsurface exploration methods available at Indian Institute of Science, Bangalore.

Keywords: Subsurface exploration, Borehole, Geophysical investigation, MASW, Ground-penetrating radar.

1.1. Introduction

Preliminary geophysical investigation of subsurface strata is important prior to tendering or execution of project and preparation of project plan of any construction. Such investigations help in proper planning, cost estimation and time bound project execution. The data from the investigation helps in identifying the types of geologic materials with engineering properties, their porosity, thickness, weathering condition for the design and planning of the project. These investigations predominantly help to plan excavation, to find out the volume of excavation material, to find out the type of material need to be excavated, properties for the foundation design, in-situ dynamic properties for the seismic analysis and also to estimate and control project cost. Proper subsurface exploration data helps to prepare Program Evaluation Review Technique (PERT) chart for project management and timely completion of the project. Inadequate, imprecise survey information can substantially impact the accuracy of estimation or a bid analogous with a certain excavation project (Stump 2004). Also, such unexpected costs can weaken the financial viability of the contractor's business. Several examples can be quoted for delay and cost escalation due to improper/wrong subsurface explorations.

Even though several advancements have taken place in geophysical testing useful for subsurface investigation and to solve unusual cases, these techniques are having poor reputation and not well accepted in geotechnical engineering due to very poor planning by engineers, ignorant of the techniques and over optimism by geophysicists. This paper presents selected study of integrated subsurface investigation using limited geotechnical and extensive geophysical investigation to solve some of the geotechnical problems. Further modern method of testing for subsurface exploration methods i.e. Standard Penetration Test (SPT) with hammer energy measurement for liquefaction assessment and Multichannel Analysis of Surface Wave (MASW) for the deep in-situ shear wave velocity measurement in deep deposits are discussed. In the integrated subsurface investigation, detailed Ground Penetrating Radar (GPR) survey with few SPT and MASW testing are carried out.

1.2. Geotechnical and Geophysical Methods

Several geotechnical and geophysical methods are useful for modern subsurface investigation. In this study widely available, simple and low cost geotechnical and geophysical methods are used. Brief summary about geotechnical and geophysical methods used in the study are presented.

The Standard Penetration Test (SPT) is one of the oldest, most popular, and commonly used in-situ tests for subsurface exploration in soil mechanics and foundation engineering because the equipments and test procedures are simple. SPT is performed by drilling out a borehole and driving a standard 'split spoon' sampler using repeated blows of a 63.5 kg hammer falling through 762 mm. The hammer is operated at the top of the borehole. It is connected to the split spoon sampler by rods. The split spoon sampler is lowered to the bottom of the borehole. It is then driven by hammer blows to a total depth of 450 mm in three intervals of 150 mm for which the number of blows is counted. The penetration resistance (N) is the number of blows required to drive the split spoon for the last 300 mm of penetration. Since the soil is considered to have been disturbed during the first 150 mm penetration, the penetration resistance for this depth is disregarded. SPT N values are useful for seismic site characterization, site response, and liquefaction studies towards seismic microzonation. In most cases, the specific site response analysis, shear wave velocity, and shear modulus (G_{max}) of layers are estimated using relationships based on the SPT N values (Anbazhagan et al. 2012a). With time, many researchers have contributed to standardize and make SPT a more efficient ground exploration test. Various corrections have been proposed for getting corrected SPT- N value of any site. Among all the corrections, energy correction is the most important. Measurement of hammer energy during SPT test is part of SPT testing in the most of western countries (ASTM D4633 2016; Anbazhagan et al. 2016) and there is a separate ASTM code (ASTM D6066 2011) to arrive at normalized N values for estimation of liquefaction potential. However, there is no such standard in the Indian code of practice for SPT testing and liquefaction assessment. Again, different code prescribes different energy correction to be applied even for same hammer and lift- release mechanism. This leads to non-uniform results. Energy correction is a very important for getting true SPT-N value of any site. The maximum theoretical energy transferred is 473.4 J. As the safety hammer energy widely used in the US has approximate 60% energy transfer, to keep the earlier data and correlations useful and valid, 60% energy transfer was assumed as standard. But multiple codes for practice and authors have reported different energy values even for the same hammer and drop mechanism. This is mostly due to different types of rods, anvil, etc. used, local site conditions, efficiency and skill of operator, etc. Hence, it becomes impractical to rely on a single value provided by an author or code to get the true value of energy correction (Howie et al. 2003). In order to measure hammer energy in the SPT setup, a simple and cost effective SPT -Hammer Energy Measuring Apparatus (HEMA) was developed by the Department of Civil Engineering, IISc, and Bangalore. SPT- HEMA is capable of recording energy at below the anvil and above the sampler tube. Figure 1.1 shows typical instrument rod and schematic field set up. In the instrumented rod the transducer records the stress variation while the accelerometer gives acceleration. These signals are received by a microcontroller which filters, amplifies the signals and processes them via Analog to Digital Convertor. A program on Lab view platform has been written to get velocity profile using acceleration data. The software uses Force-Velocity Method (FV) to integrate the product of force and velocity with respect to time as prescribed in ASTM D4633 to give final energy output.

The surface wave methods adopt these three basic steps: (1) Data Acquisition, (2) Dispersion Analysis and (3) Generating the layered-earth model considering shear and compressional wave velocities, thickness of layer, density and passions ratio, etc. Initially, surface wave methods were based on the fundamental-mode (M0) of wave and all other types of waves (higher modes, body waves, etc) were ignored. Later, this method was evolved by Matthews et al. (1996) and called as Continuous Surface Wave (CSW) method. Investigators at the University of Texas, Austin, introduced a two-receiver approach in 80's, which was based on the Fast Fourier Transform analysis of phase spectra of surface waves generated by an impulsive source like the sledge hammer. Surface wave method then became a widely used approach among geotechnical engineers and researchers.

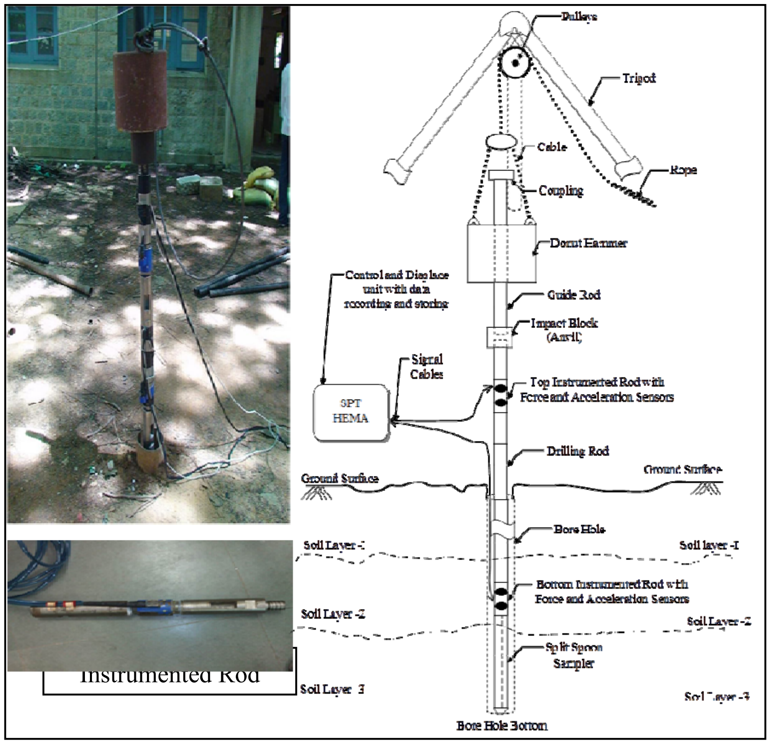

Fig.1.1. Typical Instrument Rod and Schematic Field Set Up of SPT -Hammer Energy Measuring Apparatus (HEMA)

Two receiver surface techniques were called as Spectral Analysis of Surface Waves (SASW) (Heisey et al. 1982). The complete efficiency of the method was increased by: (1) Generating multi-frequency (not mono-frequency) waves simultaneously upon impact from the seismic source and (2) Separation involved in the subsequent data processing by using FFT. It was vastly superior compared to CSW method. This method termed as "MASW" (Multichannel Analysis of Surface Waves) by Park et al. (1999) in their publication on Geophysics, became popular thereafter. The project actually started in mid-90s at the Kansas Geological Survey (KGS) by geophysicists who had been utilizing the seismic reflection method in the oil industry to image the interior of the earth for depths of several kilometers. Called the high-resolution reflection method, it was used to image very shallow depths of engineering interest. MASW method involves the measurement and analysis of the generated seismic surface waves, the result of which is the shear wave velocity profile for the surveyed area. As shear wave velocity is one of the elastic properties which is comparable with Young's Modulus, it can be used as a direct indicator of ground stiffness and consequently be used to derive the load bearing capacity. In this study, 24 Channel Geode MASW systems with 4.5 Hz and 2 Hz Geophones cable of measuring shear wave velocity up to depth of 500 m by combining passive and active survey are used.

Ground Penetration Radar, also commonly known as: EMR (electromagnetic reflection), SIR (subsurface interface radar), geo-radar, subsurface penetrating radar and soil radar, is an electromagnetic reflection method in which an electromagnetic signal is emitted via an emitter in the form of a built in antenna into the structure under inspection (Fig.1.2). As the properties of the materials vary in the substructures, the emitted waves undergo reflection. The receiver inbuilt in the antenna receives these reflected waves. These waves are recorded in the control unit, displayed on the monitor and analyzed in the computer. Frequency of emitted and received electromagnetic waves plays an important role in resolution and depth of information. Using high frequency antennas results in high-resolution data, but reduces the depth of penetration whereas, Low frequency antennas provide greater depth of penetration at the expense of lower resolution. Dielectric property being one of the most crucial parameters in non-destructive techniques can be assessed from the received EM waves. Dielectric properties are usually influenced by the volumetric properties of the subsurface layers. The electric permittivity (dielectric constant) 'ε' and the electric conductivity 'σ' are Petro physical parameters, which determine the reflectivity of layer boundaries and penetration depth. GPR is a well-established non-destructive method for investigating the internal composition of many naturally occurring materials such as rocks, earth and gravel, and man-made materials like concrete, brick and asphalt.

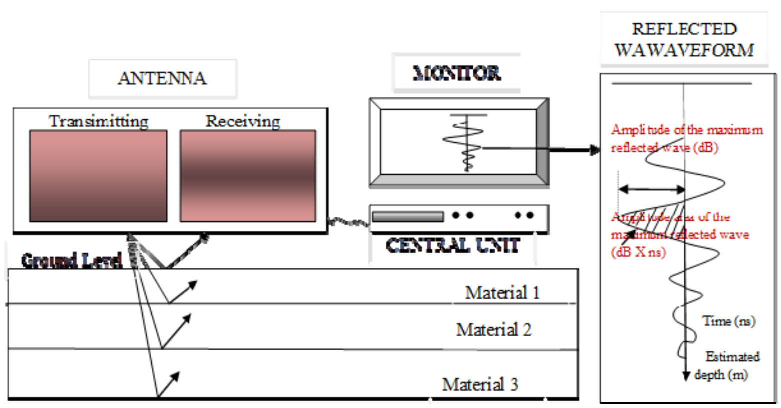

Fig.1.2. Schematic Ground Penetrating Radar Principle

GPR is being used to study the presence, depth, and lateral extent of each subsurface soil layers and is further used to classify soils (Anbazhagan et al. 2012b). Five different frequencies antenna capable of detecting pen size object to 20 m size object below ground level and also possible to investigate up to 50 m are used in this study. Most of the geotechnical investigations SPT, MASW and GPR testing are being used independently for subsurface explorations and forensic geotechnical investigations. But limited studies were carried out by integrating these tests to obtain the subsurface data for the performance evaluation of geotechnical structures.

1.3. Integrated and Modern Subsurface Investigation

Subsurface investigation plays an important role by providing suitable data for design and performance assessment of geotechnical structures. The subsurface investigations can be carried out by geological, geophysical and geotechnical methods. Many geophysical methods are engaged in the forensic investigation of geotechnical failures. In this study, seismic method of MASW, electromagnetic method of GPR and limited drilling with SPT N measurement has been used to investigate the heterogeneous compaction, undulation subsurface and Karstic Features in Lateritic Soil. Seismic methods are used to estimate the shear wave velocity of the subsurface layers and thereby Young's modulus and shear modulus. In this study, GPR has been used to identify the subsurface condition of the soil, thickness and homogeneity of the layers. The SPT results are used to get subsurface material type and depth, to compare with MASW result and to get in-situ density.

Local site-specific soil conditions have great role in amplification and liquefaction due to an earthquake. Conventional MASW active survey with 4.5 Hz geophone survey is capable of shear wave velocity up to 50 m. In this study, modern approach of combined active and passive MASW survey with low frequency geophone 2 Hz has been carried out to measure shear wave velocity more than 400 m in the deep soil deposit of Indo Gangetic Basin (IGB). Shear wave velocity measured in this study is cross correlated with drilled borehole up to depth of 350 m. Effect of hammer energy on liquefaction assessment and newly developed modern equipment SPT Hammer Energy Measurement Apparatus (SPT-HEMA) for the measurement delivered hammer energy below anvil and above split spoon sampler is also presented.

1.4. Subsurface Profiling for Excavation

Information about subsurface soil and rock layer are precisely required for proper planning and execution of excavation work in shallow bedrock sites, where variation of rock depth or boulder are found in smaller distance. Tender estimation prepared by conventional drilling was not able to identify variation of rock layers and awarded work was stalled due to the presence of hard rock layer during excavation, which was not part of tender item (Anbazhagan et al. 2017a). Client approached and requested for quantity of excavation with possible cost and time due to huge cost (about 50 lakhs) escalation demanded by contractor. MASW and GPR survey was carried out in the study area and results are validated with excavated portion. Shear wave velocity from MASW was used to find out material stiffness and GPR data was used to map variation of layer i.e thickness. Figure 1.3 shows integrated subsurface profile of typical alignment. A volume of soil and rock to be excavated was calculated and compared with the old estimated cost. The cost of excavation was obtained from integrated subsurface profile and compared with the tendered or estimated cost. In comparison (Table 1.1), it was found that the actual cost of excavation exceeded the estimated cost by 317.09 %, which is more than twice the original estimated cost. From the results it can be concluded that performing integrated subsurface prior to planning or executing a project, provides knowledge of

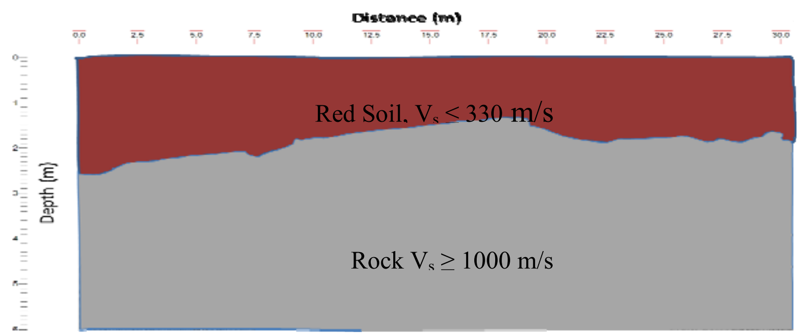

Fig.1.3. Integrated Subsurface Profile for Typical Alignment for Cost Estimation.

the geophysical or geotechnical properties of the site area which helps in estimating the exact cost of excavation, planning the orientation of the alignment and efficient use of time, manpower and machine, also accidental damage to subsurface utilities as well as excavation machinery can be avoided. More accurate volume calculation can be achieved by performing GPR surveys in the grid patterns for 3D sections (Anbazhagan et al. 2017a).

Table 1.1. Calculation of percentage escalation of actual cost from the estimated cost.

	Earthwork (cum)	*Rate (INR)*	*Rock (cum)*	*Rate (INR)*	*Total (INR)*
Old Estimated	405	245.00	0	-	99,225.00
In this study	151.875	245.00	253.125	1096.00	314634.00

1.5. Floor Slab Settlement due to Heavy Rain

Non- uniform settlement of reinforced cement concrete with polished stone floor slab and also rotation and titling of machine foundations in 5000 m^2 industrial building were investigated using SPT and GPR survey. Site visit showed that heavy rain caused excessive settlement and titling in a 95% finished building, roofing was completed, but rain water gutter was under construction. Factory was constructed in undulating ground and soil filling varies from 1 m to 8 m and most of the settlement titling was noticed in soil fill area. GPR study has been carried out in systematic manner and radargram showed homogenous and heterogeneous wave form due to subsurface. Typical GPR radargram showing uniform and non-uniform GPR wave form is shown in Figure 1.4. In order to understand wave form due to change in soil moisture and density of site specific soil, a model study has been performed. The study found that increase in moisture content reduces GPR wave amplitude and increases bulk density and dielectric constant. Uniform good reflected wave was observed in the uniform section and scattered and non-uniform wave was observed in heterogeneous section. Figure 1.5 shows GPR model results with density and moisture content. GPR results are confirmed by measuring SPT N values in the heterogeneous location. Low SPT N value i.e <15 was observed in heterogeneous section and higher SPT value i.e > 18 was observed in the uniform section. Integrated approach helped to complete investigation of larger area in short time with mapping of gap between floor slab and foundation with settled soil layer. Further area of heterogeneous zone due to settlement also arrived from GPR study. This investigation helped for effective repair and retrofits the distressed sections.

1.6. Identification of Karstic Features in Lateritic Soil

Lateritic soils are widely spread across the southern and central parts of India. Lateritic formations usually have soft sediments entrapped between the hard to medium soft lateritic rock which are leached due to the ingress of water during rainy seasons creating hollow sections or cavities which span over large lengths.

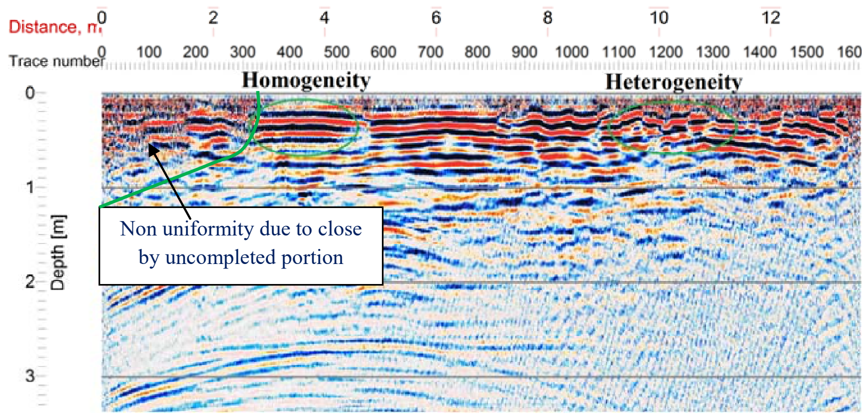

Fig.1.4. Typical GPR radargram of the subsurface with varying moisture and density

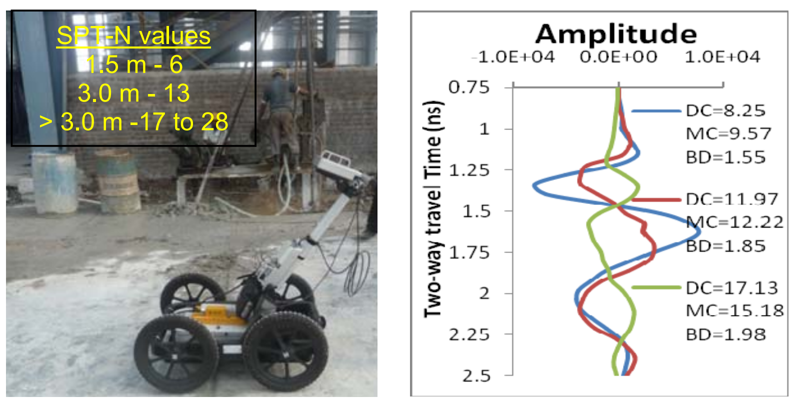

Fig.1.5. Site Photo and GPR Wave Trace for the Different Moisture Content & Density

Laterites are highly heterogeneous and prone to cavitation due to its weathering process; a sound knowledge of the subsurface condition is required before starting any construction. The integrated geotechnical and geophysical investigation has been carried out to identify the subsurface air cavities over large areas in mega project. Geophysical survey GPR and MASW techniques are used to identify the heterogeneities in lateritic soils and localized cavities. Initial GPR survey is carried out across the complete area at specific interval spacing and probable heterogeneous locations are identified. Detailed GPR and MASW surveys are carried out at probable stretches in close intervals. The anomalies in the GPR radargram are identified by visual inspection and trace amplitude approach. The results of the radar survey are crosschecked by generating 2-D shear wave velocity profile adopt-ing MASW. Typical radargram with trace amplitude and 2-D shear wave velocity contrast due to cavity is shown in Figure 1.6. This study shows that application of integrated geophysical techniques using GPR and MASW methods provides more promising results in comparison to only bore hole methods for identification of cavities in highly heterogeneous soil type like laterite over large area in mega project (Anbazhagan et al. 2017b).

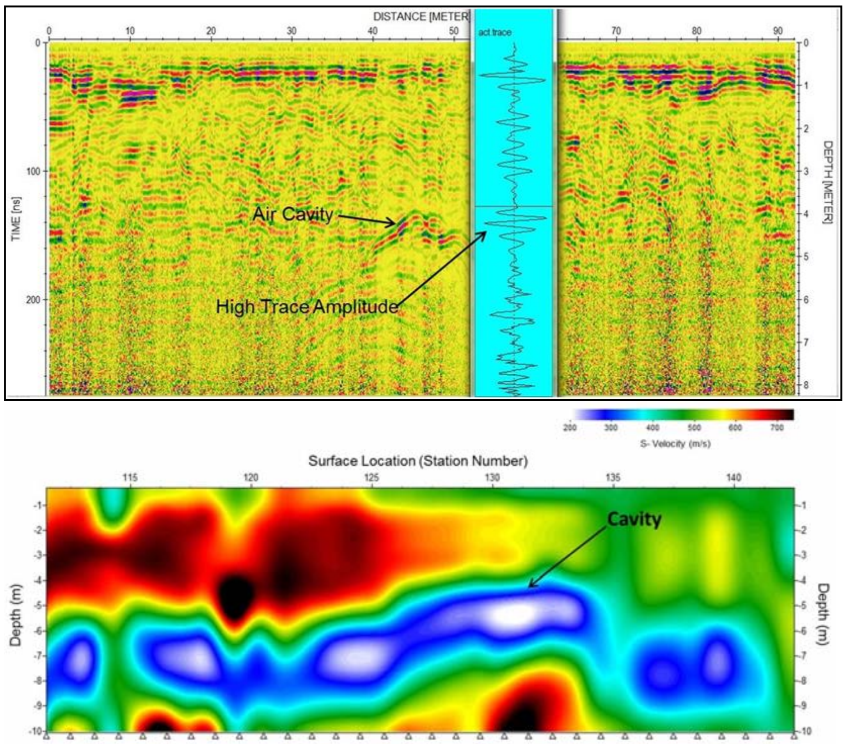

Fig.1.6. Typical Radargram Showing Cavity and Confirmed 2-D V_s Profile

1.7. Study of Indo Gangetic Basin soil by Modern Approach

The high level of seismicity associated with the Himalayan tectonic province may cause huge site amplification and liquefaction in the loose Indo-Gangetic Basin (IGB) deep alluvial deposits. Few studies were carried out to characterize the IGB soil up to shallow depth but a very limited attempt has been made to measure the dynamic properties of the deep soil column. Combined active and passive MASW using low frequency geophones has been carried out in IGB and shear wave velocity profile has been measured up to 500 m depth by this modern approach. V_s values up to 50 m were measured in the active survey. Low frequency waves are generated by heavy excavator and vehicular traffic has been used and V_s values up to 500 m are measured by passive method. Measured shear wave velocity are compared with 350 m drilled log data and bedrock depth matches with V_s values > 800 m/s. Figure 1.7 shows typical shear wave velocity of deep soil deposit with borelog.

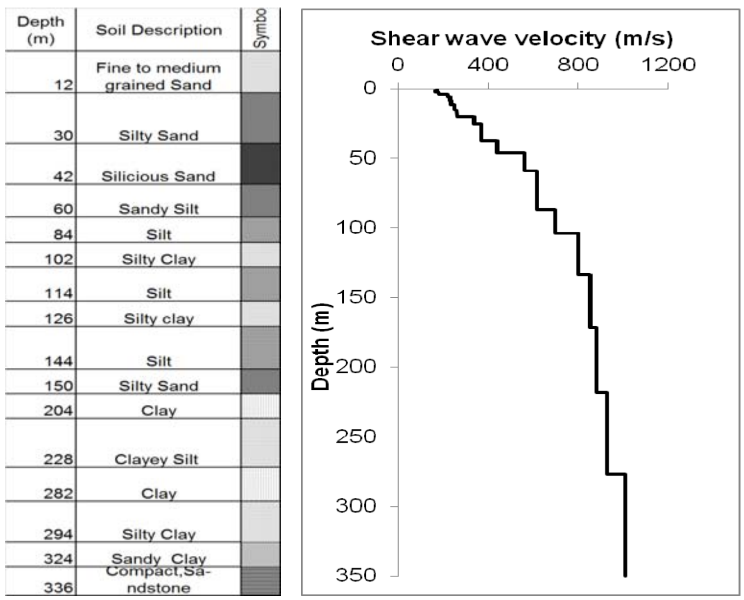

Fig.1.7. Typical Shear Wave Velocity Measured by Modern Combined Active and Passive Approach using 2 Hz Geophones

Further newly developed SPT-HEMA has been engaged to measure hammer energy delivered below anvil and above sampler. The study shows that typical donut hammer used in India has energy efficiency which varies from 68 % to 40 % and 62 % to 38 % close to sampler. Nearly 3 % to 25 % energy difference has been found between the energy measured just below the anvil and above the sampler. Typical variation of energy from a selected borehole with SPT N values are shown in Figure 1.8. Thus, considering the whole data set the energy correction factor was found to vary from 0.65 to 1.15 below the anvil and from 0.58 to 1.03 above sampler. Typical borehole data has been taken and effect of hammer energy on liquefaction potential has been estimated and detailed calculation can be found in Anbazhagan et al. (2016). The actual energy transferred plays a very crucial role in assessment of liquefaction and any uncertainty in energy transfer percentage leads to great uncertainties in the liquefaction potential of soil. This study shows that variations of hammer energy in liquefaction calculation may change soil layer category from liquefiable to non-liquefiable in the same borehole. Hence it is recommended to use actual energy measurement set-up at the site, then using some arbitrary energy correction factor for finding liquefaction at any site.

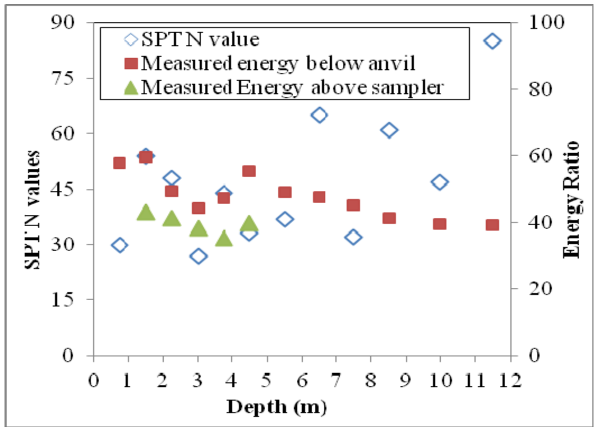

Fig.1.8. Hammer Energy during SPT Test Using Modern Facility of SPT-HEMA

1.8. Summary

Here I presented recently completed and ongoing industrial and research work on geotechnical investigation. The effective planning and execution of civil construction project requires integrated subsurface investigation, so that project can be completed in time. Integrated subsurface investigation not only useful for new project construction, but it also helps in forensic investigation of the geotechnical failure for effective retrofitting and restoration. I also presented modern approach in investigating deep soil deposit in IGB and hammer energy measurement using indigenously developed SPT-HEMA and effect of hammer energy on liquefaction estimation.

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