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Application of Geophysical Survey in Two Different Engineering Projects - Case Study

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ABSTRACT

Geological mapping provides the knowledge in planning of civil engineering projects used in the construction of dams, tunnels, underground caverns, tanks, reservoirs, highways, railways, bridges buildings and other infrastructure projects with identification of areas susceptible to failures due to geological hazards such as earthquake, landslides, weathering effects, etc. Geological and geophysical inputs help in determining the subsurface problems associated with foundation and stability of civil engineering structures and provide suitable measures for foundation design.

Geophysical methods are employed as an aid to geological investigations for assessment of in-situ conditions and engineering properties of the rock mass mainly by using seismic and electrical methods. These methods provide subsurface information which includes depth of overburden, depth and quality of rock mass, major faults, folds, dykes and water saturation conditions. Besides, resistivity measurements are also utilized for determination of the true resistivity values for the use of earth material for helping designers to carry out the safe design of powerhouse complex. Vibration monitoring studies are conducted for controlled blast design and for safe excavation of major structures. Slope stability design and analysis is carried out by utilizing the inputs from inclinometer studies.

Geophysical methods have been widely used in geotechnical work for last three decades and presently they are used with increasing frequency in various geotechnical problems. The present available geophysical techniques have been tried, tested and well documented to resolve the subsurface geological problems.

Problems with the applications of geophysics in engineering practice are seen to arise because of one or more reasons e.g., inadequate survey planning; inappropriate choice or specification of technique(s); poor execution of the geophysical survey and difficulty in interpretation.

The aim of this paper is to provide the information to the use of geophysics in geotechnical site investigations with emphasis on Seismic refraction and 2D resistivity imaging survey, its application in civil engineering projects with a couple of case studies.

Keywords: Seismic refraction; resistivity imaging; ERT; SRT; P-wave velocity; under water tunnel

1. INTRODUCTION

The science of geophysics applies the principles of physics to the study of the Earth. Geophysical investigations of the interior of the earth involve taking measurements at or near the Earth's surface that are influenced by the internal distribution of physical properties. Analysis of these measurements can reveal how the physical properties of the Earth's interior vary vertically and laterally. By selection of different scales, geophysical methods may be applied to a wide range of investigations from studies of the entire Earth to exploration of a localized region for engineering or other purposes. In the engineering geophysical exploration measurements are made within geographically restricted areas to determine the distributions of physical properties that reflect the local subsurface geology with depths.

An alternative method of investigating subsurface geology is, of course, by drilling of boreholes, which is expensive and provide information only at discrete locations. Geophysical surveying, although sometimes prone to major ambiguities or uncertainties of interpretation, however, provides a rapid and cost-effective means of deriving information on subsurface geology. In the exploration of subsurface resources, the methods are capable of detecting and delineating local features of potential interest that could not be discovered by any realistic drilling programme. Geophysical surveying does not dispense with the need of drilling but, it can optimize exploration programme by maximizing the rate of ground coverage and minimizing the drilling requirement, if properly applied. The importance of geophysical exploration in civil engineering to delineate the subsurface geological information is so high that the basic principles, scope of the methods and their main fields of application should be appreciated by any practicing Engineers or Scientist.

2. SITE CHARACTERIZATION

Accurate characterization of geology and hydrogeology of the site is the critical issue. If it becomes possible, planning of exploration would be reasonably straightforward. However, due to lack of understanding of site geology and subsurface condition, it is often responsible for unrealistic planning of site exploration causing the structural and environmental failures. If all sites were simple (horizontally stratified geology with uniform properties), site characterization would be easy. Data from just one borehole would be sufficient to characterize the site. However, in most geologic settings, this may not be the case. Even at sites where the geology appears to be uniform, one must be alert to often-subtle variations that can cause significant changes in structural or hydrological properties. Traditional approaches to subsurface field investigations commonly rely only upon the use of direct drilling and sampling methods such as:

- Borings for soil and rock samples;
- Monitoring wells for gathering hydrogeological data and water samples;
- Laboratory analysis of discrete soil, rock and water samples to provide a quantitative assessment of site conditions; and
- Extensive interpolation and extrapolation from a limited number of data points.

Soil and rock sampling programs and the planning of drilling locations are being done by educated guesswork. The accuracy and effectiveness of such an approach is heavily dependent upon the assumption that subsurface conditions are uniform. Numerous pitfalls are associated with this approach that can result in an incomplete or even erroneous understanding of site conditions. These oversights are the cause of many structural and environmental failures with increase of cost and time overrun in construction projects.

3. SEISMIC REFRACTION SURVEY

Geo-physical investigations by use of seismic refraction survey or seismic refraction tomography (SRT) are widely accepted as a non-destructive dynamic test for site characterization which enables in precise identification of rock anomalies like fractures and faults, the modulus of elasticity in shear and compression, overburden thickness, rippability (excavability) and most of the other physical properties of rock of the sub-surface strata. This technique optimizes the scope of site investigations and eliminates the uncertainties by virtue of continuous information provided rather than discrete information obtained by conventional boreholes drilling.

Seismic refraction method is used for in-situ investigations of geological problems primarily because of the seismic velocity is an indicator of density and porosity, relative quality and rippablity of rock mass. It is one of the most reliable techniques for determination of depth to bedrock. Since the propagation of compressional and shear waves is dependent on the elastic properties of the rock, therefore seismic refraction technique is being used for determining the dynamic properties of the rock at low strain. The output of seismic refraction survey is a model of velocities and depth of the subsurface layers, which can be correlated with drilling for subsurface lithological variation along with the characteristics of soil and rock. With the correlation of lithological data from borehole, seismic refraction survey provides an unambiguous interpretation reliably, rapidly. In complex geological site (faulting, buried channels etc.) borehole data alone are inadequate and could be misleading, whereas seismic refraction survey yields continuous information to resolve those problems with accurate interpretation.

3.1 Application of Seismic Refraction Tomography (SRT)

In engineering application, seismic refraction surveys are used to map the depth to bedrock and to provide information on the compressional and shear wave velocities of the various units overlying bedrock. Velocity information used to calculate small-strain dynamic properties of rock units. The commonly used techniques are seismic r efraction, MASW, cross hole seismic (V_p and V_s), vertical seismic profiling and bore hole seismic tomography. Nowadays, the high-resolution seismic reflection survey is being used for identification of shallow geological structures. For resolving the various geotechnical problems and better appreciation of geophysical techniques, it is advisable to plan at least two geophysical techniques for correlations of results and interpretations among themselves.

Major uses of seismic survey in engineering site investigations are identification of different subsoil condition, weathered, fractured and bedrock profile with structural deformation like fault, shear zone, fissures etc. through the variation in seismic velocity with depth. Seismic refraction survey is also useful in quick assessment of design parameters, dynamic elastic properties of soil & rock, assessment of foundation condition, rippablity & blast-induced damage assessment and rock mass characterization for underground excavations. In addition, it is useful in ground water evaluation in alluvial & rocky terrain, selection of sites for construction of dykes for ground water recharge structures.

3.2 Advantages of SRT Survey

Qualities of this method viz., low-cost operation, quick assessment of reliable continuous subsurface information, non-destructive in nature and great accessibility to remote region have increased its widely acceptance for in-situ investigations.

3.3 Limitations of SRT

Certain limitations like identifications of low seismic velocity units underlying high seismic velocity units, thin intermediate seismic velocity refractor and insufficient velocity contrast between two geological units need to be considered prior to using seismic refraction techniques. Moreover, even after these limitations, seismic survey is one of the most reliable tools for geotechnical investigation in civil engineering and Geo-hazard mapping.

4. 2D ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

In electrical prospecting, the conventional process of conducting sounding and profiling is time-consuming and labour-intensive. Recent development of multielectrode resistivity imaging technique or electrical resistivity tomography (ERT) combines these two techniques and produces a two-dimensional subsurface resistivity image in a very short time. It gives almost a continuous subsurface resistivity picture with vertical and lateral variation in resistivity. This is quite a fast technique used mostly to substantiate the sounding results and across the geologic structures where conventional approach of sounding or profiling may not yield fruitful results.

Resistivity imaging technique is a new development in recent years to image the subsurface with moderately complex geology and wide variations in aquifer occurrences. Such surveys are usually carried out using a large number of electrodes connected to a multi-core cable. A laptop microcomputer together with an electronic switching unit is used to automatically select the relevant electrodes for each measurement. At present, field techniques and equipment to carry out 2D resistivity surveys are fairly well developed. In a typical 2D survey setup with a number of electrodes along a straight line attached to a multi-core cable, normally a constant spacing between adjacent electrodes is used (Fig. 1). The multi-core cable is attached to an electronic switching unit which is connected to a laptop computer. The sequence of measurements to be taken, the type of array to be used and other survey parameters (such as the current to use) is normally entered into a text file which can be read by a computer program in a laptop computer. The measurements are taken automatically and stored in the computer. The data is processed by using Industry standard 2D resistivity imaging software.

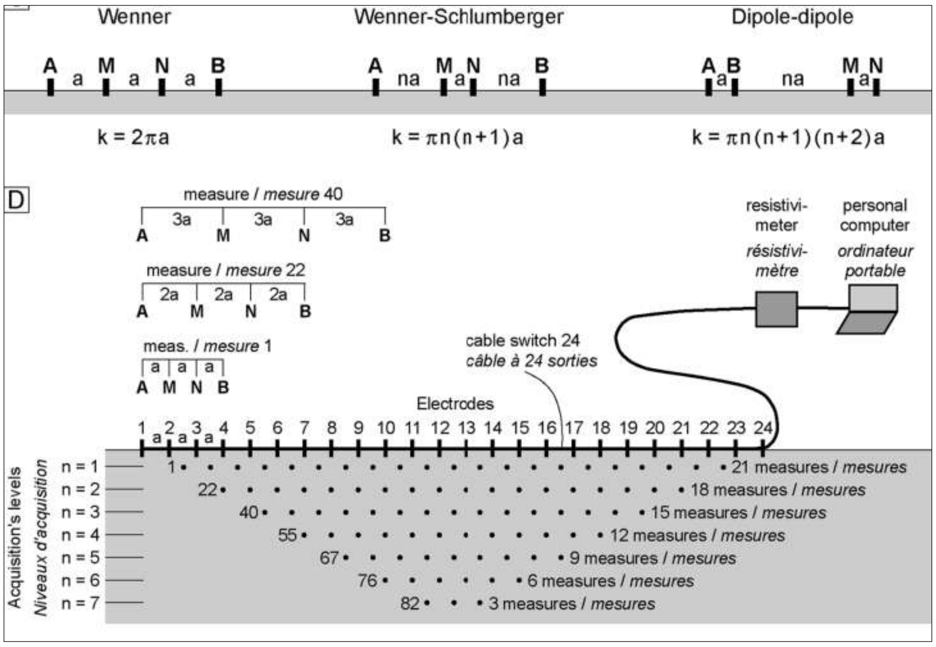

Figure 1 - Principle of 2D electrical resistivity imaging

4.1 Application of 2D ERT survey

The technique is useful in mapping complex subsurface geological formation with lateral in-homogeneities owing to the presence of resistive or conductive bodies such as dykes. The technique is used to delineate the geological contacts, faults, fracture and fissures, saturated zones within soil and cork including saline water zones and its extent both vertically and horizontally. Significant resistivity contrasts occur between dry and water-saturated formations, and formations with fresh and brackish or saline water. Sands of various grain size, clays, weathered and fractured granites and gneisses, sandstones, cavernous limestone, vesicular basalts, etc. all have defined but overlapping ranges of resistivity. The resistivity ranges for different rock types vary significantly based on local hydro geological conditions.

4.2 Advantages of 2D ERT Survey

The electrical resistivity imaging is cost-effective and non-destructive field techniques. It is effective in assessing the quality of ground water and therefore can be used to locate the saline/fresh ground water interface, or saline water pockets. Resistivity contrasts associated with presence or absence of ground water can be used to delineate the geometry of aquifers and zones favorable for ground water accumulation. This method also provides useful information on lithological characterization, depth to resistive bedrock, direction of ground water flow, orientation of fracture zones, and the locations of faults and paleo channels, as well as cavities in limestone. The method also can be used for specific environmental applications such as delineating the area and extent of ground water pollution, identifying zones suitable for artificial ground water recharge, soil salinity mapping, and reclamation of coastal saline aquifers. Although 3D Resistivity imaging survey is tedious and costly approach but provides more accurate subsurface lithology and underground aquifers. This method is useful for identification of fracture and movement of grouts and fluids in area of construction.

4.3 Limitation of 2D ERT

In normal resistivity survey certain limitations like overlapping resistivity ranges and a very wide range of resistivity makes it difficult to characterize subsurface lithology and its interpretation by their resistivity values unless standardized locally. Also, the accuracy and resolution of the response decreases with increasing depth and decreasing contrasts in resistivity. The presence of very high or very low resistivity surface soils can affect interpretation. While the former increases the contact resistance, the latter masks the signals coming from deeper layers. The presence of such soils can attenuate a considerable percentage of the input signal going into the subsurface, as well as the output signal coming back from deeper zones. Moreover, with the development of electronics in the Geophysical instrumentation, the modern equipment may overcome all constrains for many complex geological situations of the subsurface. The accuracy and its acceptability have been tested globally for engineering Geophysical problems.

Underground metallic utilities/conductors such as pipelines, electric cables underground and overhead both running close and parallel to ERT profile may severely affect the inverted resistivity sections which may lead to the ambiguity in interpretation.

5. PROJECTS UNDER STUDY

5.1 Case Study 1 – Under Water Tunnel Project

Details of continuous under sea subsurface seismic refraction survey to assess subsurface geology for the design of undersea railway tunnel across the Thane creek are given under following headings:

5.1.1 Survey procedure

In this survey, a marine refraction exploration technique was used. The air gun was used as a seismic source and the bay cable consisting of numerous hydrophones as receivers used was a marine seismic cable that was installed on the water bottom (Fig. 2). Two units of bay cable with 590m in length with one unit incorporating 60 hydrophones at 10m interval were deployed.

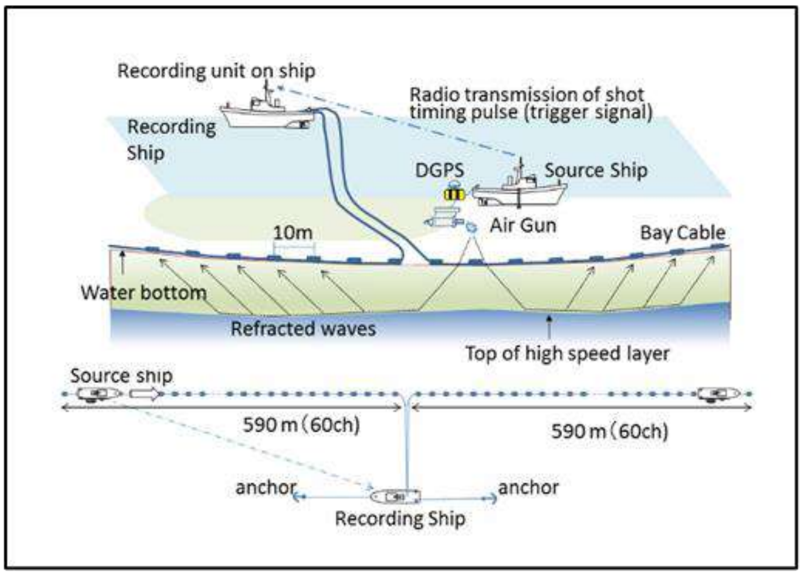

Figure 2 - Schematic diagram of marine seismic refraction survey arrangement

The position of the source was controlled by differential global positioning system (DGPS). The position of all receivers was determined by the same principle as the hypocenter determination using the arrival time of the direct water wave generated from the source. In this calculation, the depth of the receiver was fixed to the depth of the water bottom which was subjected to tidal correction.

5.1.2 Equipment details

The geophysical equipment deployed for marine seismic refraction work are given in Table 1.

Table 1 - Equipment used for marine refraction survey

Equipment /System	Description / Model / Resolution
Positioning	GPS System: R110(x2), A100(x1), (hemisphere), DSM232(trimble)
Software / navigation	Nav Log (Marimex, Japan)
Single beam echo sounder	PDR-1300, 200kHz (Senbon Denki)
Air gun	PAR AIR-GUN 600B (40 cubic inches) (Bolt, USA)
Source energy	nitrogen or air cylinder (15MPa or 20MPa); capacity 47 litre (x3)*/day
Receivers	bay cable of 590m in one unit, and 60 hydrophones (60ch) are attached to one unit at equal intervals of 10 meters; two units were used to make 120 channel in this survey. (Mark Products, USA)
Seismic data acquisition	Geode (Geometrics, USA) 24ch/unit x 5 units
Automatic tide gauge	indigenous product of KGE ,Japan
Underwater sound velocity meter	Smart SV/P (AML Oceanographic)
Radio for trigger signal	VX-212 (Standard)
Software for analysis	KGE's software; MODELING for analyzing 2D seismic refraction data; 3D-TOMO for analyzing 3D seismic refraction tomography

5.1.3 Data output and results

Refraction results indicate four layered model with variation in velocity with thickness. Refraction depth probe reveals that the area is generally covered by 1.18m to 55.19m thick layer of overburden sea sediment with highly to completely weathered basalt, having seismic velocity of the order of 1600 m/s to 2200m/s.

This is followed by the first intermediate layer of moderately weathered and jointed basalt; having seismic velocity of the order of 2800m/s to 3500m/s. Higher velocity indicates weathered and jointed/fractured basalt. Thickness of this layer along the profile line is varying from 5.0m to 30.64 m.

This is further followed by slightly weathered to fresh less jointed basalt, having seismic velocity of the order of 4000m/s to 4200m/s. Thickness of this layer along the profile line is varying from 5.27m to 33.58m. which is overlain by a fourth refracted layer having seismic velocity of the order of 4600 m/s to 5000m/s, indicates presence of fresh basalt. Bathymetric section, seismic data and interpreted section is placed at Fig. 3.

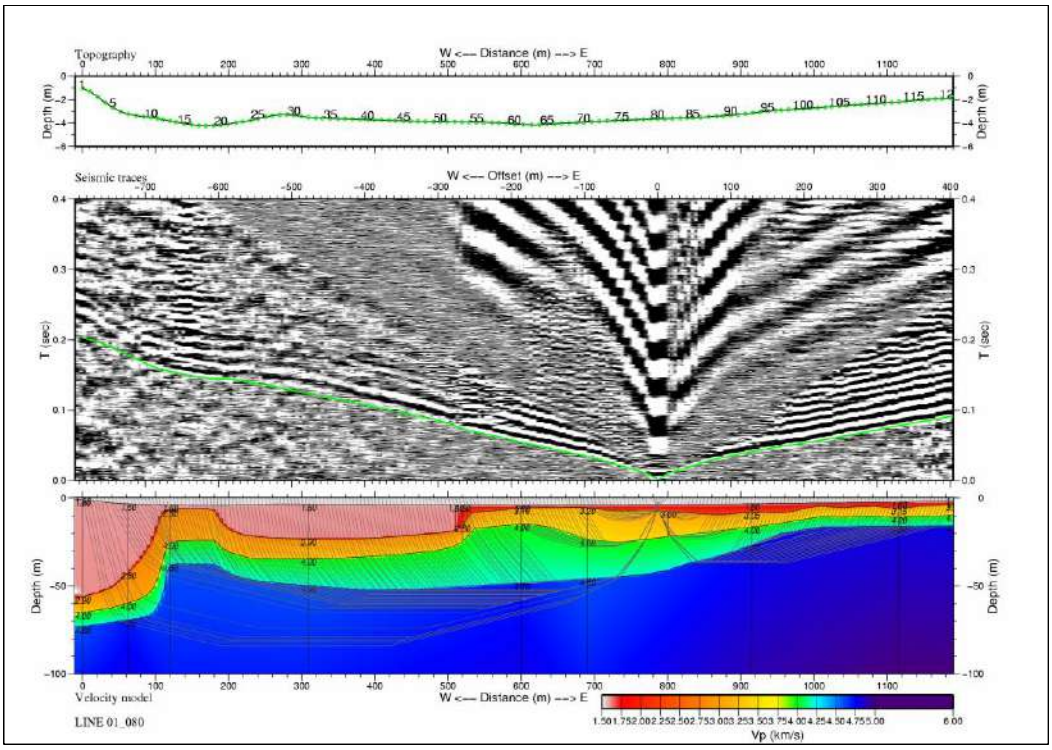

Figure 3 - Bathymetry, refraction data and processed section

5.1.4 Correlations

Seismic Section has been correlated with drilling results and a reasonable match has been observed with drilling data as presented in Fig. 4.

5.1.5 Engineering properties of rock mass

Based on the seismic velocity, rock mass quality 'Q' value has been obtained using Eq. 1. The Barton's Q value can further be used for the rock mass classification. Equation 2 proposed by Barton (1995) is used for estimating rock mass rating (RMR) of Bieniawski (1989) from Q. Equation 3 is for estimating the uniaxial compressive strength of rock material rock mass strength (σ_c) in MPa.

$$Q = 10^{\left(\frac{Vp-3500}{1000}\right)} \quad \text{(Barton, 1991)} \quad (1)$$

$$RMR = 15\, logQ + 50 \quad \text{(Barton, 1995)} \quad (2)$$

$$\sigma_c = \{(0.035 * Vp) - 31.5\} \quad \text{(Freyberg, 1972 in Garia et al., 2020)} \quad (3)$$

The rock mass is classified as per both Q-system (Barton et al., 1974) and the Japanese rock mass classification standard for Mountain tunnel (JRTT, 2008). Japanese rock classification and the standard of support system have been developed based on the elastic wave velocity (Vp in km/sec). On the basis of seismic velocity (Vp) and Q value of different layers, an overall appraisal of Q, RMR, the rock mass classification and intact rock strength (σ_c) have been assessed and given in Table 2.

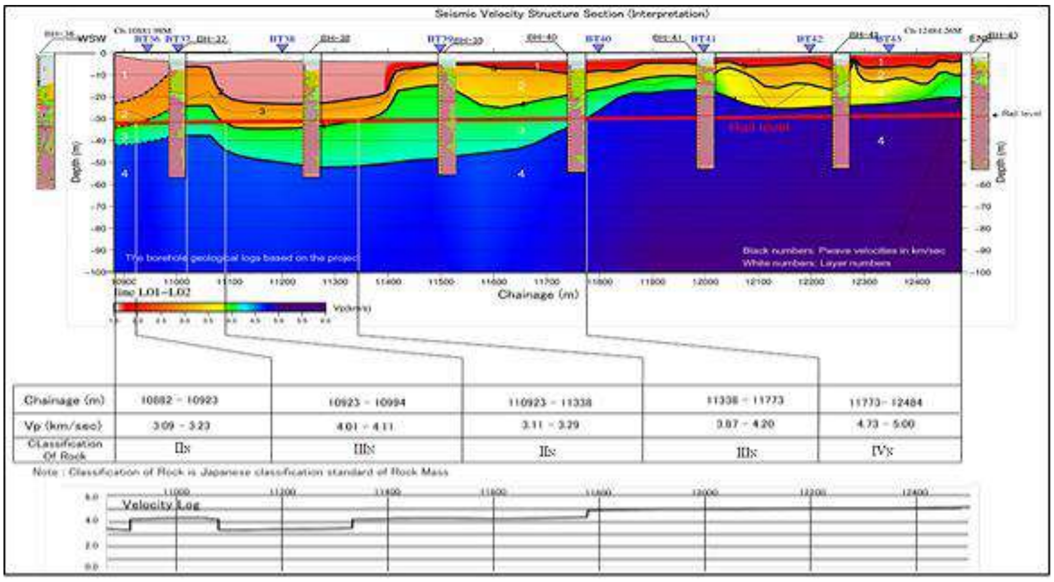

Figure 4 - Correlation of seismic section with drilling data

Table 2 - Seismic velocity with interpreted lithology and rock mass properties

Layer No.	Velocity V_P (m/s)	Thickness (m)		Q	RMR	Intact rock strength σ_c in MPa	Interpreted Lithology	Rock mass classification based on Barton's Q value	Japanese Rock mass classification (JRTT, 2008)	
		From	To							
1	1600 to 2200	1.178	55.19	0.01 to 0.05	22 to 31	24.50 to 45.50	Sea sediment with highly to completely weathered basalt.	Extremely poor	-	-
2	2800 to 3500	5.0	30.64	0.20 to 1.00	40 to 50	66.50 to 91.00	Weathered and jointed/Fractured basalt.	Very poor	I N to II N	Rock type A
3	4000 to 4200	5.27	33.58	3.16 to 5.01	58 to 61	108.50 to 115.50	Slightly weathered to fresh Less jointed basalt.	Fair	III N	Rock type A
4	4600 to 5000	-	-	12.59 to 31.62	67 to 73	129.50 to 143.50	Fresh basalt.	Good	IV N	Rock type A

5.2 Case Study 2 - Canal Project

5.2.1 Project background

Sleemanabad right bank carrier canal between 104 km 129 km in the Narmada Basin located in the south of Katni town. The proposed canal works are part of the Bargi diversion project which envisages construction of 194km long canal for augmenting irrigated agriculture in the surrounding villages. Out of 25km stretch between km 104 and Km 129 of the canal alignment, about 12km stretch between Km104 and Km116 is underground which is under construction by using tunnel boring machine.

Prior to Construction geotechnical investigation were carried out through drilling, sampling and testing at 63 nos. boreholes for subsurface stratification and design of the tunnel. During construction of tunnel between Ch. 107.792km and Ch. 110.965km, very high hydrostatic pressure and seepage conditions have been observed at about Ch. 107.792km. Due to discrete geotechnical information, tunnelling progress has been hampered and almost stopped (Clark, 2019).

5.2.2 Objective and scope of work

The aim of 2D ERT survey was to establish the continuous subsurface stratification and thickness through variation in resistivity both laterally and vertically along the problematic zones of tunnel alignment with assessment of subsurface stratification overlying the bed rock and its characteristic for the construction of proposed underground tunnel. To investigate the problem; 11 nos. of ERT profiles were planned along the problematic section.

5.2.3 Geology of the study area

Katni district in which Sleemanabad belongs is underlain by various geological formations, forming different types of aquifers in the area. Main geological units of the area are Archaean, Mahakoshals, Vindhayan Super group, Gondwana super group, Lametas, Deccan traps, Katni formation, Laterites and alluvium.

The geology along the tunnel alignment changes frequently. It consists of compact residual soils, silts, alluvium, highly weathered limestone and dolomite, with stretches of slate, massive crystal- line limestone and fresh marble. Ground water table is above the tunnel for the entire length.

5.2.4 Data output and results

Three ERT sections from Figs. 5 to 7 are presented to illustrate the findings through 2D resistivity imaging survey and results are placed at Table 3.

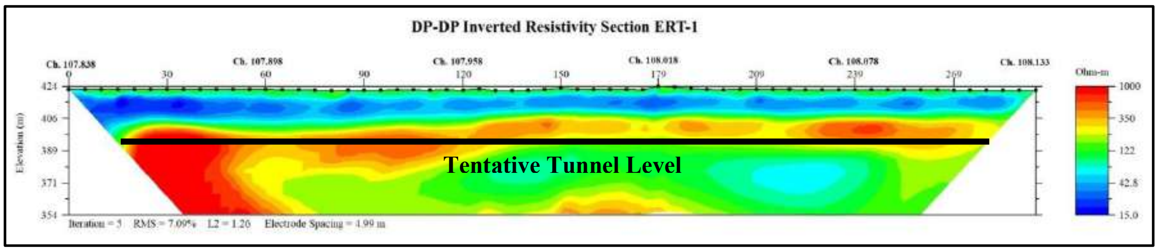

Figure 5 - ERT-1 Section along the alignment between Ch. 107838m to 108133m

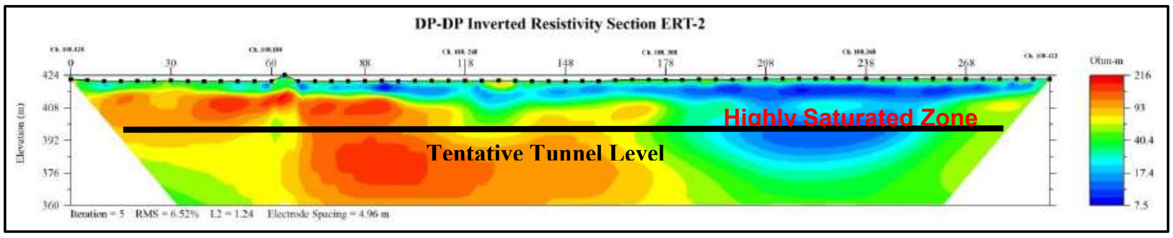

Figure 6 - ERT-2 Section along the alignment between Ch. 108128m to 108422m

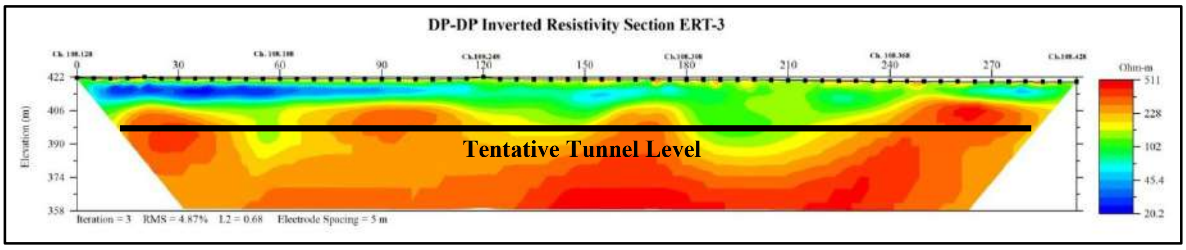

Figure 7 - ERT-3 Section along the alignment between Ch. 108422m to 108716m

Table 3 - Interpreted results showing lateral variation of resistivity with depth & inferred lithology

ERT Section	Layers	Resistivity Range (Ωm)		Lateral Distance (m)		Thickness (m)		Interpretation of Lithology
		From	To	From	To	From	To	
ERT–1	1	55	115	0.0	295	2.27	6.14	top alluvial soil
	2	11	40	0.0	295	2.52	10.58	clay/silty sand under saturation
	3	>40	105	0.0	295	2.77	7.56	stiff to very stiff residual soil
	4	127	464	10	294	7.58	29.42	moderately to slightly weathered marble / slate; lower resistivity of the order of 127Ωm to 350 Ωm indicates highly weathered & disintegrated marble/slate
ERT–2	1	12	54.6	0.0	67	4.89	6.99	Top alluvial soil
				67	295	2.26	3.0	
	2	10.3	40	68	295	6.27	66.96	clay/silty sand under saturation
	3	61	216	10.5	170	33.38	58.94	highly to completely weathered and disintegrated rock
ERT–3	1	90	204	0.0	295	1.85	4.71	top alluvial soil and high resistivity indicates dry nature of overburden
	2	22	57	4.3	115	4.37	8.58	clay/silty sand under saturation/stiff residual soil
	3	65	123	7.8	289	2.3	24.73	very stiff residual soil with highly to completely weathered rock mass
	4	>123	510	10.9	288	37	60.2	moderately to slightly weathered marble / slate; lower resistivity of the order of 123Ωm to 350 Ωm indicates highly weathered & disintegrated marble/slate

6. CONCLUSIONS

On the basis of detailed geophysical investigations carried out at two different civil engineering projects, following conclusions may be drawn:

6.1 Underwater Tunnel Project using ERT

- At tunnel grade, seismic velocity of the order of 3500m/sec to 4200m/s interpreted as slightly weathered to fresh less jointed to basalt, strong in nature with Q value varies from 1.0 to 5.01 and RMR 50 to 61 and rock mass strength (σ_c) varies from 91MPa to 115.5MPa categorized as “Very poor to Fair” with rock mass grade “II_N to III_N”.
- Seismic velocity of the order of 4600m/s to 5000m/sec interpreted as fresh basalt, strong in nature with Q value varies from 12.59 to 39.81 and RMR 67 to 73. Rock mass strength (σ_c) varies from 129.5MPa to 143.5MPa categorized as “Good” with rock mass grade “IV_N”.

- The rock mass characterization obtained from seismic survey may be adopted for tunnel excavation methodology and design of support system. During construction of tunnel if any ambiguity in interpretation is observed; then in that case TSP (Tunnel ahead seismic survey) is recommended in those stretches.

6.2 Canal Project using ERT

- At ERT-1, at tunnel grade highly weathered & disintegrated to moderately to slightly weathered marble /Slate is anticipated.
- At ERT-2, Highly to Completely weathered and disintegrated Rock along with low resistivity zone interpreted with Clay/Silty sand under saturation is anticipated at tunnel grade.
- AT ERT-3, at Tunnel grade moderately to slightly weathered Marble / Slate is anticipated. Lower resistivity of the order of 123Ωm to 350Ωm indicates highly weathered & disintegrated Marble/slate.
- Tunnel alignment at ERT -1and 2 passes through mixed geological formation featuring weak and saturated zones therefore, adequate support system should be considered during design with dewatering facilities to release of excess hydrostatic pressure during construction.
- Tunnel alignment along ERT-3 passes through almost homogeneous subsurface materials with moderate strength rock mass at tunnel grade therefore, normal tunneling is expected. However, due to poor rock mass condition permanent support is recommended.

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