Integrated Geophysical Investigations for Site Characterisation Along a Hydro Tunnel Under Low Overburden Conditions

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Abstract

Information regarding rock mass quality, hydrogeological conditions and presence of weak zones within the excavation zone is crucial for safe and economical design of any tunnel. Usually the rock quality is assessed by drilling, direct observation of core samples and parametric evaluation of sample properties as obtained by laboratory testing. Drilling results are sometimes elusive as it provides only localised information in areas with obscure geology. Extensive drilling is both cost-prohibitive and time consuming. Under such situations, surface geophysical methods such as Electrical Resistivity and Seismic Refraction Surveys come to rescue as they provide a more pragmatic assessment of the subsurface rock mass condition. These methods can also map weak zones (faults, fractures, cavities, weathered and water bearing zones, etc.) which are often characterised by lower resistivity and/ or lesser seismic velocity than the surrounding medium.

This paper discusses a successful application of integrated geophysical investigations using 2D electrical resistivity imaging and seismic refraction methods for assessing the nature of overburden as well as the rockmass conditions along the head race tunnel of the Kumaradhara Mini Hydroelectric Project in Karnataka, India. The proposed head race tunnel of this hydel project is 1000m long and 7m in diameter with cover varying from 5-45m above the crown of the tunnel. Geophysical investigations were carried out with a view to estimate the overburden thickness, map the hard rock profile and delineate the weak zones along the tunnel alignment upto a depth of 40m. Based on reliable information obtained from the results of the twin geophysical surveys, the tunnel alignment was frozen.

Keywords: *Electrical resistivity imaging, seismic refraction survey, bed rock, weak zones, overburden*

Introduction

Insufficient information and unforeseen conditions in the rockmass in and around the tunneling medium can lead to time and cost overrun of construction projects. A thorough investigation of the subsurface geological and hydrogeological conditions can facilitate design guidelines for better planning of construction activities. The investigations should include evaluating both overburden and bedrock vis-à-vis the tunneling medium. Some key issues like rock type, weathering, fracturing, rock cover, presence of water and shear or fault zones have to be examined in detail (Einstein et al., 1978; McCann et al., 1997). Direct methods like drilling and laboratory testing of core samples are preferred in shallow-depth ground investigations. Combination techniques using state-of-the-art equipment and data processing techniques in engineering geophysics makes it possible to meet the desired objectives with high resolution (Burger, 1992; Heikkinen and Saksa, 1998). The aim of geophysical site characterisation is to prepare an engineering geological prognosis for the civil construction site by analyzing the geological, structural and physical conditions of the rock mass so that detailed information is available for different

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stages of construction (Takahashi, 2004). Geophysical technique is the only way to remotely and non-destructively examine the shallow subsurface for the requisite engineering properties of the rock mass. Several integrated geophysical studies had been carried out by Hayashi and Takahashi, 2001; Surendra, 2007; Soupios, et al., 2007 and Bekler, et al., 2011 in the past for investigating these types of problems.

In the present study, detailed geophysical investigations using 2D electrical Resistivity Imaging (RI) and Seismic Refraction (SR) Survey were carried out for deciphering the nature of the overburden materials and mapping the bedrock profile along the Head Race Tunnel (HRT) of the proposed Kumaradhara Mini Hydroelectric Project (KMHEP) at Bandady village near Mangalore (NIRM Report, (2009). The project area lies between the Western Ghats and the Arabian Sea, with Mangalore in the north and Manjeswar in the south. This hydel project envisages constructing a 5m high weir across river Kumaradhara to utilise a head of 20m to generate 18MW of power. The water conductor system includes a 700m long approach canal that feeds a circular HRT of 1000m length and 7m dia. The overburden thickness above the tunnel level varies from 5m to 45m. As part of the subsurface investigations along the HRT alignment, two RI profiles of 376m each and twelve (8 along the alignment and 4 across the alignment) SR profiles of 115m each were surveyed. The part plan showing the survey lines in the study area is shown in Fig.1. The depth of investigation was 40m for SR and 60m for RI survey.

Geology of the area

Regionally, the area exposes Precambrian Peninsular gneissic terrain and major rock types are gneissic granites, granites,

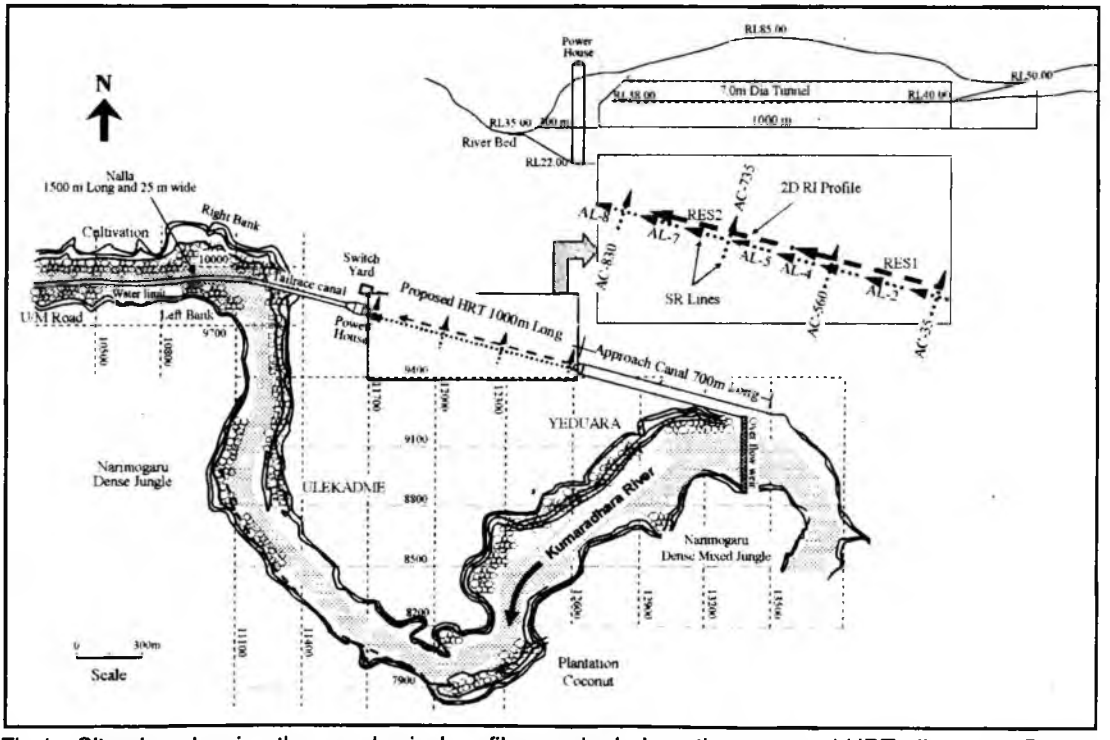

Fig.1. Site plan showing the geophysical profiles marked along the proposed HRT alignment. Dotted lines show alignment for SR survey (AL1 to AL8, AC-35, AC-560, AC-735 and AC-830) and dashed lines show that of RI survey.

dolerites, gabbros and granulites with migmatites and biotite-hornblende gneisses. These intrusives are composed of amphibolites, pyroxene-granulites and calc-granulites. In the study area, gneissic granite is the main rock. Laterites are commonly found above the gneiss as capping, which is much less developed in the project area than other parts of the region where their thickness is more. The thickness of the laterite layer in the study area varies from 2-10m whereas the weathered rock layer is 5-10m thick. The rocks have undergone intensive weathering leading to kaolinisation. At few locations weathering has also propagated into the deeper part of the hard rock possibly through the fracture plane.

Survey methods

As stated earlier, both RI and SR survey was carried out in the study area. Of them, RI was intended to give the true resistivity distribution in the subsurface and SR was intended to generate the picture of the subsurface seismic velocity distribution. Both these methods are briefed here.

(a) Resistivity Imaging (RI): RI is applied to study the subsurface resistivity distribution in areas of complex geology (Griffiths and Barker, 1993; Reynolds 1997). Qualitative assessment of the subsurface rock mass including the mapping of bedrock has been previously carried out using RI studies by Chen et al., 1996, and Gilson et al., 2000. In the present case, 2D-RI was carried out by using SYSCAL R1 Plus (48 channel) equipment with electrode spacing of 8m. Dipole-dipole electrode configuration is used as it is very sensitive to horizontal changes in resistivity and can provide reasonable depth of investigation as well (Loke, 2000). Two RI profiles RES1 and RES2 were surveyed with profile lengths of 376m each with an end on tie. It may be noted that the starting point for the resistivity profile RES1 is 25m after the start of the seismic profile AL1.

(b) Seismic Refraction: The underlying theory of seismic refraction implies sending shock waves (vibrations) into the ground either by use of hammer striking a steel plate or with the use of explosives. These vibrations while traveling down get refracted back to surface and are recorded by a seismograph through an array of geophones (Redpath, 1973). Each shot provides information of the underlying medium; several shots are often needed to map geologic anomalies in terms of seismic velocity distribution (Green, 1974; Libby et al, 1970). A typical spread needs a minimum of seven to nine shots to determine the subsurface physical properties in terms of seismic velocities. In the present work, eight SR profiles of 115m each were surveyed along the tunnel alignment with an end on tie and 4 additional transverse lines were surveyed perpendicular to the tunnel alignment at chainages 35m, 560m, 735m and 830m respectively (refer Fig.1). Sensors (10Hz vertical geophones) were spread at 5m interval and shots were taken using a 10kg sledgehammer. A 24-channel seismograph of ABEM make was used to gather data (9 shots per profile) with auto-stacking (8-12 shots per location). A record length of 409ms was collected at a sampling frequency of 50ls.

Data Processing

Processing of resistivity data started with the preparation of the pseudo-section which is a contour of the measured apparent resistivity. Subsequently forward resistivity calculations were executed by applying an iterative inversion algorithm based on Finite Element Method (FEM) (Burnett, 1987; Dittmer and Szymanski, 1993). 2D-RI data was processed using RES2DINV (Loke, 1997) software. The inversion program divides the subsurface into a number of small rectangular prisms and attempts to determine the resistivity values of the model prisms by minimizing the difference between the

calculated and the observed apparent resistivity values (Loke and Barker 1996). In the present case robust model inversion constrain was used in processing and the mean RMS errors for the two RI profiles were 5% and 9.3% respectively for RES1 and RES2. Such high RMS error could be due to high heterogeneity in the area under investigation.

For processing the seismic data, the first break (travel time) was manually picked to ensure correctness. This travel-time data was then inverted using ?t-V method (Gebrande and Miller, 1985) to generate an initial velocity model. The ?t-V method is based on CMP sorted travel times and assumes multiple horizontal layers with constant interior velocity gradient. This method is useful in identifying smaller features with velocity variations and works even in case of velocity inversion (Rohdewald, 1999). The final velocity model was generated by Wavepath Eikonal Transform (WET) algorithm (Schuster and Quintus-Bosz, 1993). In this scheme of turning ray inversion method, continuous depth vs. velocity information for all the profile stations is obtained. The output from the data processing software is plotted by SURFER in terms of contours of seismic velocity at different depths along the profile line. The seismic velocities are directly related to the quality/ strength of the rock mass (Barton,

Table- 1: Classification of rock type based on resistivity values.

Sl. No.	Classification	Resistively (m)	Description
1	Type-1	15-300	Overburden, highly disintegrated rock in saturated condition, clay mineralization
2.	Type-2	300-1000	Highly weathered rocks in unsaturated condition, compact layer. Fractured Rock
3.	Type-3	1000-4000	Jointed rock mass
4.	Type-4	4000-6000	Hard Rock with few fractures
5.	Type-5	6000-1000	Massive Rock devoid of major fractures

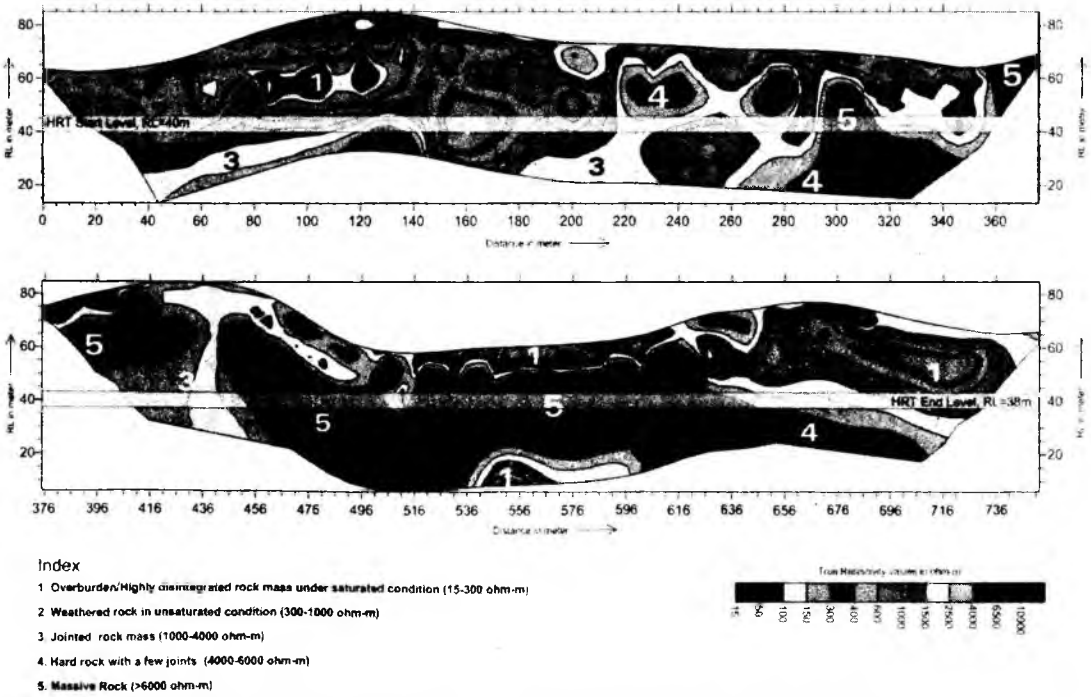

Fig.2: The true electrical resistivity sections showing different resistivity zones along the HRT alignment (a) RES1 or first portion and (b) RES2 or second portion

2007). The resulting seismic section is then interpreted accordingly in terms of seismic velocity variations in different strata types.

Discussion of Results

The subsurface resistivity distribution along the two resistivity profiles RES1 and RES2 is shown in Fig.2. In order to interpret the variation of resistivity values, the subsurface sections are divided in five major zones (based on their resistivity values) marked as 1, 2, 3, 4 and 5 on the resistivity sections. Table-1 shows the classification of rock types based on the range of resistivity values.

The type-1 zone is observed in the RES1 profile between chainage 60-170m below ground level and at two positions (middle and end) of the RES2 profile. Patches of alternating high and moderate resistivity values seen close to the surface in the first 200m of the RES1 profile and the last 70m of the RES2 profile might be due to the presence of boulders, disintegrated rock under water saturated conditions. Type-2 zone represents more compact layers including highly weathered gneisses and is more prominently mapped in the first half of RES1 profile. Type-3 zone is geologically the de-stressed or jointed rock mass and is mainly mapped below RL=55m in the second half of RES1 profile and consistently all along the profile RES2. Type-4 and Type-5 rocks are mapped in the second half of RES1 and all along profile RES2. They form the major part of the tunneling medium. Most of the subsurface is showing good quality hard rock in RES2 profile with the resistivity grater than 6500Ùm. Deteriorated rock condition with abnormally low resistivity was identified within the tunneling medium between chainage 145-175m in RES1.

The results of seismic refraction survey are interpreted based on the seismic wave velocity in the subsurface medium. For the sake of classification of subsurface layers, four ranges of seismic P-wave velocities were indexed for overburden (CS), weathered rock (WR), jointed (or de-stressed) rock (DSR) and hard rock (HR) layers. Overburden comprising compact soil with embedded rock fragments was indexed with seismic P-wave velocity range of 500-1500m/s, weathered rockmass layer with seismic wave velocity range of 1500-2500m/s, jointed rockmass layer with velocity range of 2500-3500m/s and layers with seismic velocity above 3500m/s were classified as hard rock. Seismic section pertaining to profiles AL1 and AL2 line segments of HRT alignment is shown in Fig.3.

In the seismic section along profiles AL-1 and AL-2 (fig.4), the compact soil layer and weathered layers are seen more or less following the same trend from the start to end, with soil layer thickness varying between 2-

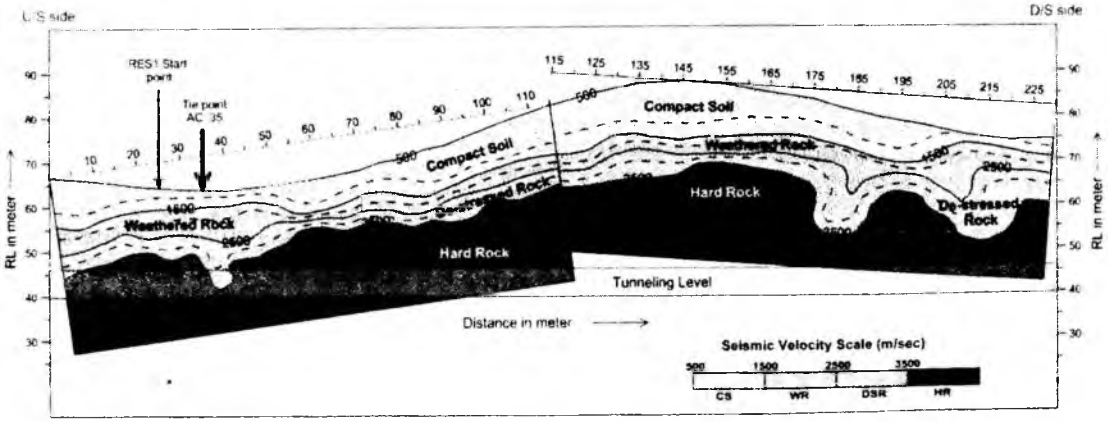

Fig. 3: Seismic subsection along profiles AL1 (0-115m) and AL2 (115-230m) along the HRT alignment of KMHEP.

8m and that of weathered rock layer between 3-5m. With the classification system adopted here, it is obvious from the seismic section that the tunnel alignment between chainage 0-50m falls below jointed rockmass layer (poor rockmass condition). Hard rock layer has an undulating trend, but it appear consistent below RL=50m. Deteriorated rock condition with associated low velocities above the crown of the tunnel is mapped between chainages 30-50m in AL1 and 170-220m in AL2. Seismic sections pertaining to lines AL3 to AL8 shows shallower rock levels and lesser undulations in the hard rock and jointed rockmass layers.

Apart from longitudinal section, four transverse lines at chainage 35m, 560m, 735m and 830m were surveyed perpendicular to the tunnel alignment to examine the lateral cover of the bed rock. One such section pertaining to crossing at chainage 560m is shown in Fig.4. This line runs parallel to a nallah (local stream). The overburden layer consisting of compact soil and weathered rock layer is 4-8m thick along this line. The jointed (de-stressed) rock layer is seen at a depth of less than 5m in the profile beginning which later increases to more than 10m towards the end. Hard rock is seen below RL=52m in the beginning which later dips up to RL=45m in the middle of the profile. From the location of the HRT marked in Fig.4, it is clear that the rock cover above the tunnel is only about 15m at this location. The disposition of layers matches well with the longitudinal crossing of line A6, thus indicating that there is no significant lateral variation in the profile of the hard rock.

Average depth of hard rock layers in all other transverse lines was about 20m. No anomalous trend was observed in any of the transverse profiles, thereby indicating that the proposed HRT alignment was quite suitable for the tunneling.

Conclusions

Resistivity imaging and seismic refraction survey over the HRT alignment successfully delineated the overburden thickness and

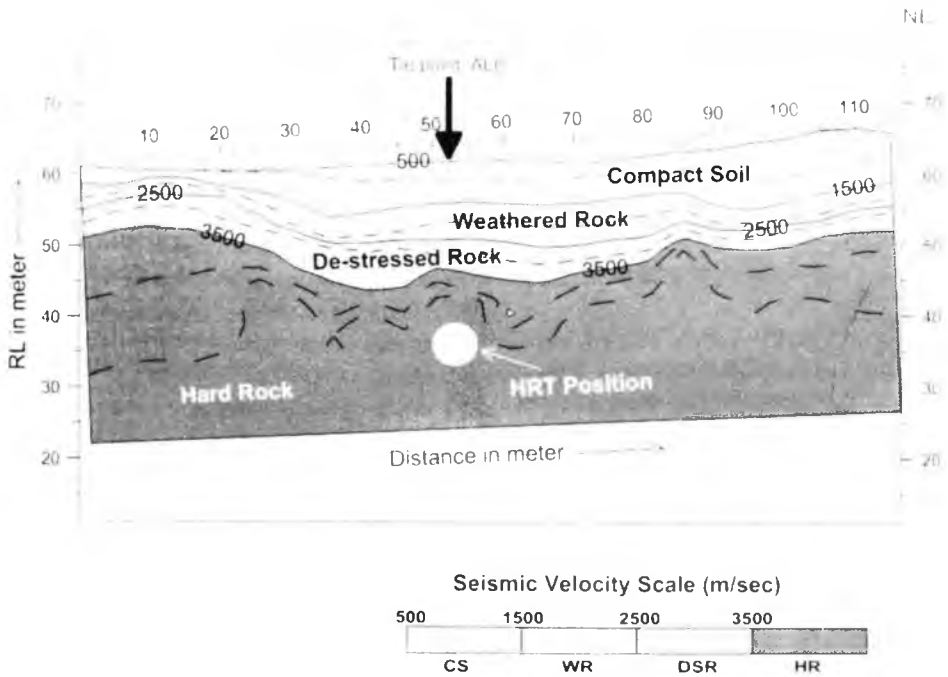

Fig.4: A typical transverse profile (AC_560) across HRT alignment of KMHEP

identified pockets of deteriorated rock conditions within the hard rock layer. Seismic survey showed that as against the tunnel crown level at RL=47m, the hard rock layer was present between RL=55-70m along most of the tunnel alignment. In the first 100m of the HRT alignment, the tunnel crown was running into the jointed rockmass layer and hence support system need to be planned accordingly.

The subsurface resistivity distribution along the first 200m of the alignment showed that the rockmass around the proposed tunnel was in the water saturated condition. A comparison with the corresponding seismic section shows a higher seismic velocity at the same level. This could be due to water-saturation of the subsurface strata. Another low resistivity pocket at tunneling level was found between chainage 140-180m where even the seismic section showed a depression in hard rock. Tunneling in this portion–(165-210m) of the HRT might encounter poor or water charged conditions. Hence it was suggested that appropriate care may be taken. Beyond the chainage of 225m, rock conditions along the tunnel alignment were better and it was expected that tunneling along this stretch might not face any geological problem.

A good correlation between resistivity imaging and seismic sections showed that the twin geophysical methods provided a better appreciation of the tunneling medium as compared to drilling or other geological investigations.

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