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Use of Appropriate Geophysical Technique for Subsurface Assessment

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ABSTRACT

The use of appropriate geophysical technique is generally a two-step approach. In step-1, potentially useful geophysical techniques are identified on the basis of the nature of the engineering problem. This is summarized in update reference table and provides initial high grading of application. In step-2, the most appropriate geophysical technique is selected based on site-specific criterion such as the depth of the target, required resolution, site accessibility and cost. This is an aid to the geo-scientists about commonly employed geophysical techniques and provides information for evaluating their utility as geotechnical site characterization. The aim of this paper is to provide the guidance for use of appropriate geophysical techniques in geotechnical site characterization based on geophysical survey conducted at some project sites and the published literatures.

Keywords: Subsurface assessment; Geotechnical; Geophysical techniques; Case study

1. INTRODUCTION

Geophysical techniques provide useful and cost-effective information about the subsurface features of interest at the required levels of spatial resolution and target definition. The techniques are routinely applied to engineering problems of a geotechnical nature (Anderson, 2006). Geophysical data, if properly acquired, processed and interpreted can be transformed into site specific subsurface geological models (Anderson et al., 2008). These site specific models can provide information similar to that obtained from drillholes (ASTM, D5753, 2011).

The purpose of this paper is to provide the basic understanding of application of geophysical techniques used for geotechnical site characterization at the shallow subsurface of the earth, typically upto depths of less than 30 m. Geophysical techniques are designed to measure specific parameters that can be used to generate physical property models of the earth. Gravity meters, for example, measure spatial variations in the gravitational field of the Earth, and are used to generate density models of the shallow subsurface. These density models, if properly constrained, can often be transformed into geologic models with varying degrees of sophistication (Sirles, 2006).

Geophysical techniques are not a substitute for boring or testing, but it is often a very cost-effective and reliable means of imaging the subsurface between and below boreholes and for determining the in situ bulk properties of rock and soil. Reconnaissance geophysical investigations can also be used as the basis for making better selection of feasibility of site locations. The techniques may be highly significant, if used in conjunction with drillholes. Geophysical techniques may provide information about the larger area of interest and few drillholes may be drilled at specific locations to decipher sub-surface geological information. The number of drillholes may be reduced drastically, thus economizing in time and cost both.

Geophysical investigations for geotechnical site characterization in many instances enhance the reliability and speed of geotechnical investigations and reduce the cost of the whole investigation. However, geophysical techniques are not always capable of meeting the objectives as requirements of geotechnical engineers. The subsurface geological assessment delineated by geophysical methods is qualitative assessment rather than quantitative. The subsurface targets of interest may be too small or deep to resolve or impossible to effectively image information because its physical properties are too similar to those of the surrounding rocks or soils. Moreover, if enough contrast in physical properties is not available, geophysical interpretations may be inaccurate because of their inherent none uniqueness. The day to day development and advancement of technology in portable digital data acquisition systems have increased the efficiency and versatility in evaluating underground conditions and geotechnical site characterization. For example, the development of digital data acquisition systems, imaging systems and analytical software has resulted in eliminating the human errors and reduction in time of interpretation of data.

2. GEOPHYSICAL TECHNIQUES

Geophysical techniques are indirect methods of exploration in which changes in certain physical properties such as magnetism, density, acoustic, electrical resistivity, elasticity or combinations of these are used as an aid in geotechnical site characterization (Telford et al. 1990). Subsurface geological information by exploratory drifts, drillholes, test pits and in-situ testing identifying local anomalies can be applied to limited extent. However, geophysical techniques may be employed for expeditious and economical means of supplementing information that might not be identified by other methods of exploration (Kearey and Brooks, 1994). Typical uses of geophysical technique include determination of the depth of bedrock, rippability of rock, depth of ground water table, limits of organic deposits, presence of voids, location and depth of utilities. In addition, geophysical technique can also be used for stiffness and dynamic properties required for dynamic numerical analysis (Benget, 1984). Geophysical technique can be performed on the surface, in boreholes (down or cross hole), or in front of the TBM during excavation (Report No. FHWA-NHI-10-034, 2009).

The appropriate geophysical technique for geotechnical site characterization should be chosen based on the following:

i. objective of investigations,
ii. resolution required,
iii. depth of penetration required,
iv. physical property to be defined,
v. geology of the area, and
vi. nature of target and host material.

It is already proved that in most of the cases used for single geophysical technique will not reveal desired results. It is, therefore, recommended to use an integrated approach to uniquely resolve the particular problem/issues (Rana, 2014). Description of various geophysical techniques potentially used for geotechnical site characterization on the basis of the nature of engineering problems are identified and given in Table 1.

Based on the past field experiences, the geophysical techniques applied in different geological terrain and faced/ identified real field problems. It appears that the selection of appropriate geophysical technique for geotechnical site characterization is site specific. Therefore, it is important that all available potentially suitable methods are critically evaluated. The following are the key considerations while applying a geophysical technique for geotechnical site exploration programme (ASTM D6429, 2011):

i. identification of important physical properties of rock mass,
ii. identification of geophysical techniques responding to the identified physical properties,
iii. selection of geophysical techniques, which can provide the required spatial resolution and target definition,
iv. identification of geophysical techniques, which can perform well under study-area conditions,
v. cost effective analysis of the selected techniques,
vi. identification of the techniques, which can provide complementary data,
vii. assessment of geophysical control that is required to constrain the interpretation of acquired geophysical data, and
viii. cost effective analysis of overall geophysical programme.

Table 1- Potential application of geophysical techniques

Application	Seismic refraction	Seismic reflection	Seismic tomography	GPR	Electrical resistivity	MASW	ReMi
Mapping lithology	A	B	-	A	B	A	A
Mapping bedrock topography/depth of bed rock (trough, pinnacles)	A	B	-	-	B	A	A
Location of fractured rock and / or shear zones and fault	A	B	A	-	B	-	-
Mapping cavities, tunnels	B	A	A	B	B	B	B
Estimating rippability	A	-	B	-	-	B	B
Locating buried drums, pipelines and other ferromagnetic objects	-	-	A	A	-	-	-
Determining in-situ rock properties (bulk, shear and Young's moduli)	A	-	A	-	-	A	A
Estimating in-situ rock properties (saturation, porosity, permeability)	-	-	-	-	A	B	B
Mapping archeological sites (buried ferro-magnetic objects, fire beds, burials, etc)	-	-	-	A	-	-	-
Depth of water table	A	B	-	-	A	-	-

Notation: A - Primary choice and; B - Secondary choice or alternate technique.

Selection of appropriate tools should be based on site specific targets. Table 2 presents a range of choices available to address the various geotechnical issues. Few of these geophysical techniques applied on Indian projects are discussed in this paper.

Every technique has its specific applications and limitations. The ground penetrating radar (GPR) method may be used for a variety of civil engineering, ground water evaluation and hazardous waste site applications (Daniels, 1996). It provides subsurface information ranging in depth from several tens of meters to a fraction of a meter. GPR technique may be integrated with other geophysical and geologic data for comprehensive site assessment. Ground penetrating radar works best in dry sandy soil where deep water table exists. Generally, penetration of radar waves is reduced by a shallow water table, high clay content of the subsurface, and in areas where the electrical resistivity of the subsurface is less than 30 ohm-m (Olhoeft, 1986).

Table 2 - Specific applications of geophysical techniques

Geophysical technique	Site conditions (Strengths)	Site conditions (Weaknesses)	Spatial resolution and target	Effectiveness of technique	Cost consideration
Seismic refraction	Very high	Low-Intermediate	Intermediate	Very high	Intermediate
Seismic reflection	High	Intermediate	Intermediate	Very high	Intermediate
Electrical resistivity	Very high	Low – High	Low – High	Very high	Very High
Ground penetrating radar	High	Low-Poor	Intermediate-Very High	Very high	Low
Seismic tomography	Very high	Low-Poor	Intermediate-High	Very high	Low
ReMi (Refraction micro-tremor)	High	Low	Intermediate-High	Intermediate	High
MASW	High	Low	Intermediate-High	Very high	Low
Magnetics	Very high	Low	Low – High	High	Low
Gravity	Very high	Low	Low -Intermediate	Intermediate	Low

The resistivity of soils varies dramatically for various soil/rock types. However, coarse dry soils tend to be more electrically resistive (low conductivity) than fine and wet soils. Common rocks show similar trends dependant on the available pore space and water content, as well as the electrical conductivity of the water filling the pore space/fractures. Table 3 shows the commonly observed ranges of electrical resistivity for rocks and soils.

Table 3 - Typical electrical resistivity values for different soil and rock types

Material	Resistivity (Ohm-m)
Clay	* 3-30
Saturated organic clay or silt	† 5-20
Sandy clay	* 5-40
Saturated inorganic clay or silt	† 10-50
Clayey sand	* 30-100
Hard, partially saturated clays † and silts, saturated sands and gravels	† 50-150
Shales, dry clays, silts	† 100-500
Sand, gravel	* 100-4000
Sandstone	* 100-8000
Sandstones, dry sands and gravels	† 200-1000
Crystalline rocks	* 200-10000
Sound crystalline rocks	† 1000-10000
Rocksalt, anhydrite	* >1100

*Notations: * - Values from Dohr (1975); † -Values from Sowers and Sowers (1970)*

Cross-hole tomography can be utilized to decipher the information viz. presence of shear zones, cavities, voids etc. in between two drillholes. This involves recording seismograms with a source in one borehole and detectors in another. Seismic tomography has become a standard geophysical tool to investigate the velocity variations in any kind of geological environments. High resolution maps of seismic tomography are now the best solution to prepare representative geologic cross section between any two drillholes.

3. APPLICATIONS OF GEOPHYSICAL TECHNIQUES

3.1 Soil/Unconsolidated Layer

This application includes determining the depth, thickness and areal extent of unconsolidated layers. These layers may be discontinuous or include lenses of various materials. These layers can be detected because of differences in their physical properties as compared to adjacent materials.

3.2 Depth of Bedrock

This application includes determining depth to the top of competent rock covered by unconsolidated overburden layer. The choice of geophysical technique depends on whether there is a physical property contrast between the rock and the overlying material. In the areas where the exposed rock is weathered or highly fractured, bed rock may be difficult to determine. Highly irregular exposed rock surfaces may pose additional problems in geophysical survey. The depth of loose soil over rock is needed in analysis of debris as it slides slowly.

3.3 Depth of Water Table

This application includes determining the depth at which a subsurface geological formation is fully saturated. The water table (top of the saturated layer) can be detected because of the changes in physical properties that are caused by saturated conditions. The ability to detect the water table may depend on the geologic formation in which it occurs. Geophysical seismic refraction techniques can be used to detect the water table in most unconsolidated materials, whereas electrical resistivity and electromagnetic or GPR technique may be used to detect the water table in either consolidated or unconsolidated formations.

3.4 Fractures and Fault Zones

This application includes the location and characterization of joints, fractures, and faults. These features range from individual joints and fracture zones to larger regional structural features. Joints, fractures and fault zones may be dry, fluid-filled or filled with clays or weathered rock. The detectability of these features increases with the size of the feature and with the presence of distinctive pore fluids or conductive fill material.

3.5 Voids and Sinkholes

This application includes karst features, such as weathered depressions in rock, open voids, water-filled, or sediment-filled sinkholes and cavities or larger cave systems. In many cases, the target of concern may be beyond the effective resolution or depth range. Deep cavities show signs of their presence in the near surface and may be interpreted using shallow geophysical data. The ability to detect cavity size decreases with increasing depth for all surface geophysical techniques. It is required for the design of foundations.

3.6 Soil and Rock Properties

This application refers to the measurement of the physical properties of soil and rock viz. elastic, inelastic, plastic and electrical. The choice of the geophysical technique selected will be determined by the specific property to be measured. For example, rippability and acoustic velocities of rock are measured by surface geophysical seismic refraction survey. The dynamic modulus is measured between boreholes by seismic tomography, whereas soil resistivity is measured by electrical resistivity survey.

3.7 Dam and Lagoon Leakage

This application refers to the detection and mapping of fluids leaking along preferential flow pathways from a dam or lagoon bodies. The application of surface geophysical techniques to detect leakage is contingent upon the presence of localized flow or difference in conductivity.

4. CASE STUDIES

4.1 Geotechnical Characterization for New Spillway at Kabrai Dam

The Arjun Sahayak Project located in Bundelkhand region of U.P. state envisages diverting 73.6 cumec (m^3/s) water from Lachura dam to Arjun reservoir, through 38.6 km long feeder canal and 62.32 cumec water from Arjun reservoir to Kabrai dam, through 31.3 km long feeder canal. The Kabrai dam was built in the year 1995 across Magaria and Kulahari rivers between Rachiya and Dharaun hills. The existing earthen dam is 15.24 m high and 2.24 km long. In order to accommodate the additional water in Kabrai dam, it is proposed to raise the height of the existing Kabrai dam by 12.0 m. At present, the Kabrai dam has a spillway with a flankscape on its left side. Raising the earthen section of the dam by 12.0 m will require construction of a new spillway structure with an increased height replacing the old spillway. To decipher the bed rock profile in the area of interest, geophysical seismic refraction survey in conjunction with electrical resistivity survey were conducted**.**

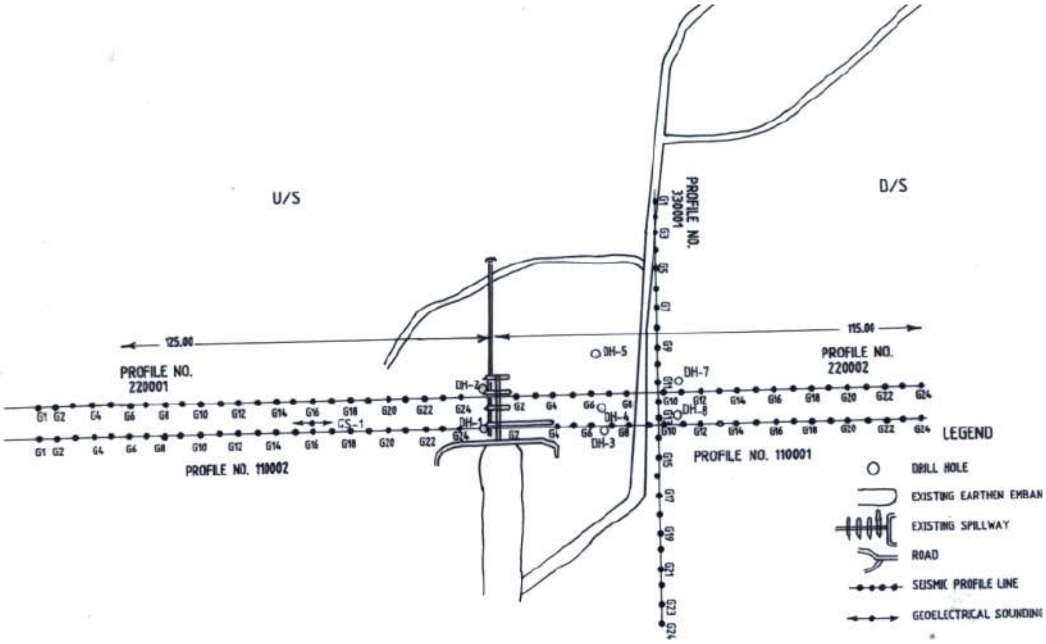

Fig. 1 - Location map of geophysical survey at Kabrai dam, U.P.

The seismic refraction survey was conducted using a 24-channel seismograph and blasting as source of energy for generation of seismic wave. A total five seismic lines, four across old spillway and one parallel to the old spillway were conducted along three seismic profiles. One geo-electrical sounding was conducted along the seismic profile No. 110002. Figure 1 shows the layout of the project area and seismic survey lines and geo-electrical sounding points. Two parallel seismic profiles of length 240 m each with 5 m geophone interval were conducted across the old spillway. The first seismic profile consists of two seismic lines 110001 and 110002, whereas second seismic profile consists of seismic lines 220001 and 220002. Third seismic profile of length 115 m with same interval consists seismic line 330001 conducted along the road site, nearly parallel to dam axis. The locations of each seismic profile lines are given in Fig. 1. Photograph showing seismic refraction and electrical resistivity survey conducted in the field is given in Fig. 2.

a) Seismic refraction survey   b) Electrical resistivity survey

Fig. 2 - Seismic refraction and electrical resistivity survey at Kabrai dam, U.P.

The survey results are presented in P-wave velocity profiles with reduced levels and presented in the form of geoseismic section is given in Figs. 3, 4 & 5.

These profiles assisted in deciphering the subsurface stratigraphy, bedrock quality and weak zone in bed rock with depth (CSMRS, 2010). Results of seismic refraction survey are shown in Table 4**.** The geoelectrical sounding (GS) were conducted to delineate the unconsolidated formations overlying the basement rock.

Seismic refraction along the river indicated P-wave velocity of the first layer as 700- 1400 m/sec, thus confirming overburden and highly weathered rock formation. The P-wave velocity of the second layer was 4900 - 5300 m/sec indicating good quality bed rock as second layer**.** The depth of the first layer varies from 5 m to 12 m. Seismic refraction survey across the river bed showed P-wave velocity of the first overburden layer as 500-1250 m/sec whereas it was observed as to be 2500-4100 m/sec in the second layer indicating weak zone in bed rock.

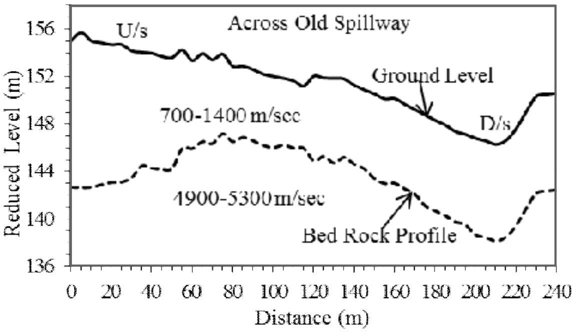

Fig. 3 - Geoseismic section of profile numbers 110001 & 110002

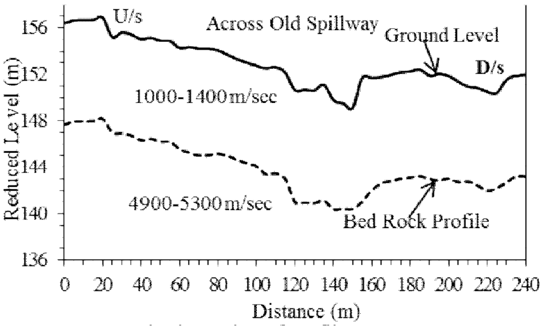

Fig. 4 - Geoseismic section of profile numbers 220001 & 220002

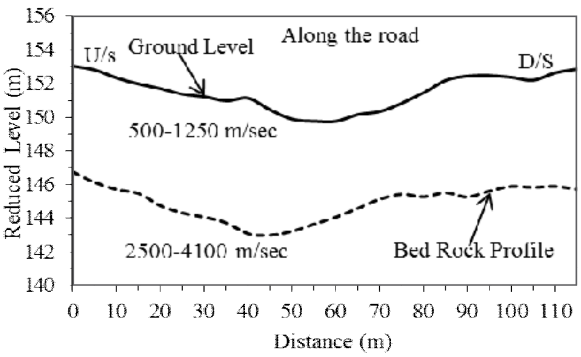

Fig. 5 - Geoseismic section of profile number 330001

Table 4 - Interpreted results of seismic refraction survey

S. No.	Profile No.	Variation in 1st layer		Variation in 2nd layer	
		Seismic velocity (m/sec)	Depth (m)	Seismic velocity (m/sec)	Depth (m)
1	110001 & 110002	700 -1400	5.0 to 12.0	4900-5300	5.0-12.0
2	220001 & 220002	1000 -1400	7.0 to 9.0	4900-5300	7.0-9.0
2	220001 & 220002	1000 -1400	5.0 to 8.0	4900-5300	5.0-8.0

Geoelectrical Sounding (GS) with Schlumberger electrode configuration was carried out. The sounding was conducted with the maximum current electrode separation (AB) of 90 m only, due to the spread constraint. Current electrode separation were expanded in steps of 1.0 m up to AB/2 = 12 m and then in steps of 5 m up to AB/2 = 45 m onwards, with appropriate MN separation. The values of apparent resistivity (ρ_a), the product of resistance and geometric factor) in ohm-m were plotted against the related half-current electrode separation on double logarithmic scale paper of moduli 62.5 mm. The curve was carefully smoothened for the interpretation. Preliminary quantitative interpretation of VES curve was attempted by semi empirical 'Auxiliary point' method with the help of two-layer master curves and auxiliary point charts of Orellana–Mooney. The interpreted result gives the resistivity of different layers and the depth of various interfaces underneath. The data was also processed and interpreted on IPI2Win to verify the manually interpreted result. Any deviation of the computed curve from the related field curve was modified keeping in view of the local geology to arrive at a realistic model. The true resistivity values, thickness and depth range are given in Table 5.

Table 5 - Interpreted results of geo-electrical sounding data

True Resistivity (Ohm-m)	Thickness (m)	Depth Range (m)	Inferred Geology/Sub-surface Layers
$\rho_1 = 125$	1.22	0.00-1.22	Top surface layer/overburden
$\rho_2 = 448$	11.8	1.22-11.8	Hard semi-consolidated formation
$\rho_3 = 9722$	---	11.8	Hard formation/bed rock

The interpreted true resistivity of the field VES curve indicates 3 sub-stratum geo-electrical layers. The resistivity sounding curve obtained in the area is of H or HA type. The resistivity of the 1st layer was 125 Ohm-m with thickness of 1.22 m, representing top surface layer/overburden. Resistivity of the 2nd layer was 448 Ohm-m and thickness is 11.8 m indicating weathered rock/ hard semi-consolidated formation. The 3rd layer was having resistivity of 9722 Ohm-m representing hard rock formation/bed rock.

The geophysical technique employed at the project site proved to be an economical tool for geotechnical site characterization for construction of new spillway.

4.2 Seismic Refraction Survey on Exposed Bouldary Bed at Ujh Multipurpose Project, J&K

The Ujh multipurpose project envisages the construction of a 30 m high diversion barrage for irrigation with nearly 7.7 km long head race tunnel (HRT). The project area is located on the river Ujh, near Village Jakhole, District; Kathua of Jammu and Kashmir (J&K). The barrage is a diversion structure the foundation of which should be geotechnical sound to sustain the load of the structure and water pressure in the reservoir.

The geophysical seismic refraction surveys were conducted using 24 channel seismograph for site investigation of proposed barrage at Ujh multipurpose project. Seismic refraction survey for a total length of 846 m on the left bank consisting of 6 spreads of 138 m was conducted (CSMRS, 2011). The right bank was inaccessible. Three seismic profile lines consisting of six seismic lines were conducted along the proposed alignment of barrage axis and one seismic profile line was conducted across barrage axis as shown in Fig. 6.

Since the area was covered with exposed boulders, it was difficult to fix the geophones. Hence, geophones were planted in plastic bucket filled with sand and the same was embedded in the ground as shown in Fig. 7. The interpreted results of seismic survey are presented in P-wave velocity profiles with reduced levels (RL) in the form of geoseismic section (Figs. 8, 9 & 10).

Geoseismic section of profile lines on the left bank confirmed the seismic velocity of the first layer as 600- 1300 m/sec with thickness varying from 6 m to 40 m. Geophysical interpretation inferred the first layer (top surface layer) as overburden consisting of boulders filled with sand, gravels and pebbles. It was also observed that the materials were densely packed. The seismic velocity of the second layer was found to be 2400 - 2600 m/sec, interpreted as weathered rock/ weak rock mass. The seismic P-wave velocity of 4000 m/sec or more could not be found up to 50 m depth in any profiles. Geophysical survey can be effectively used for geotechnical site investigation quickly and economically for locating the suitable barrage site. Based upon the geophysical investigation by seismic refraction surveys, the barrage site was shifted downstream of the proposed location.

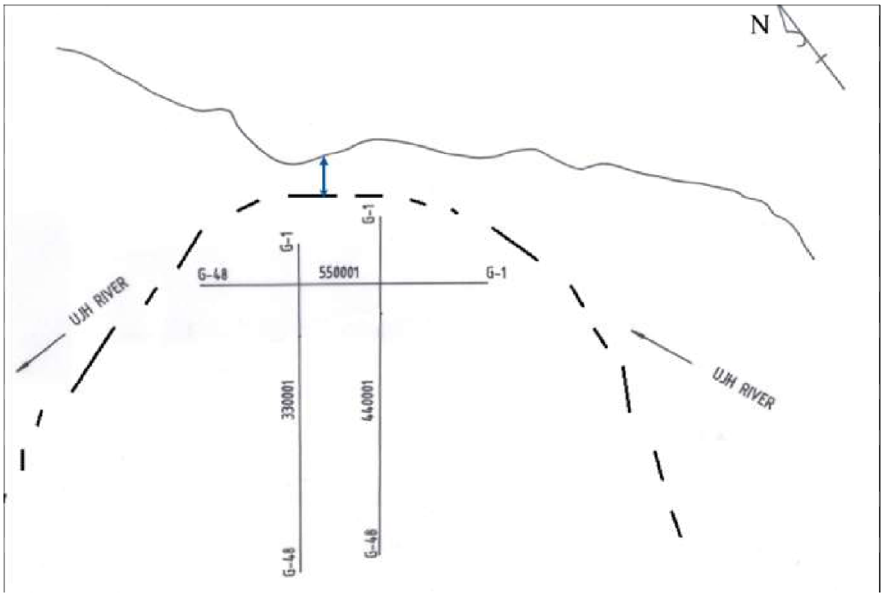

Fig. 6 - Layout plan of seismic profile lines at Ujh barrage project, J&K

Fig. 7 - Arrangement to fix geophones in exposed bouldary surface

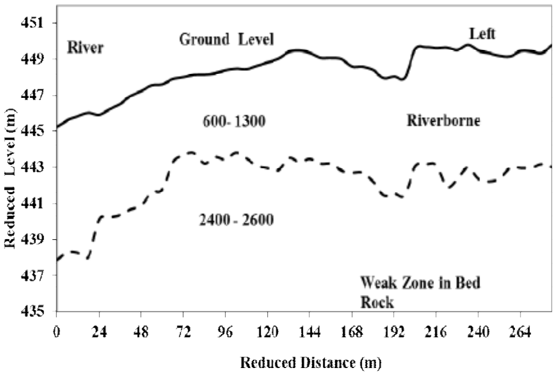

Fig. 8 - Geoseismic section of profile numbers 30001 & 330002

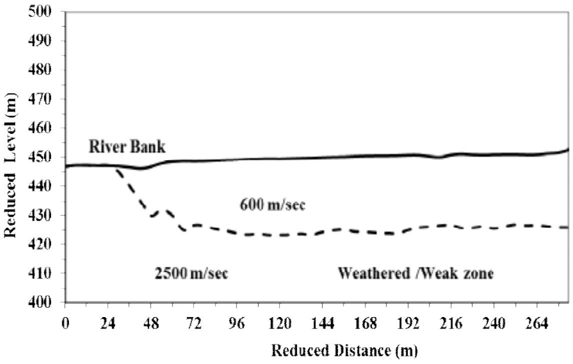

Fig. 8 - Geoseismic section of profile numbers 440001 & 440002

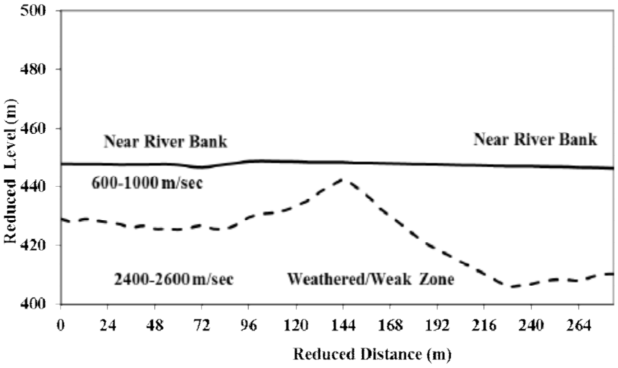

Fig. 8 - Geo-seismic section of profile numbers550001 & 550002

5. CONCLUSIONS

- The selection of preferred geophysical technique for a number of common applications depends on objectives, topography and field conditions (Table 1).
- The rating system is based upon the ability of each technique to produce results under average field conditions when compared to other techniques used for similar application.

- The final selection must be made considering site specific conditions and the field experiences.
- Proper selection of the geophysical technique suiting the working field conditions and the interpretation may help the designers in optimization of design.

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