IRC:123-2017

GUIDELINES ON GEOPHYSICAL INVESTIGATION FOR BRIDGES

INDIAN ROADS CONGRESS
2017

GUIDELINES ON GEOPHYSICAL INVESTIGATION FOR BRIDGES

Published by:

INDIAN ROADS CONGRESS

Kama Koti Marg,
Sector-6, R.K. Puram,
New Delhi-110 022

NOVEmBER 2017

Price : ₹ 600/-
(Plus Packing & Postage)

First Published : November, 2017
Reprinted : June, 2019

Printed by India Offset Press, Delhi - 110 064
300 Copies

CONTENTS

LIST OF TABLES

LIST OF FIGURES

PERSONNEL OF THE BRIDGES SPECIFICATIONS AND STANDARDS COmmITTEE

(as on 24th June, 2017)

1	Kumar, Manoj (Convenor)	Director General (Road Development) & Special Secretary to Govt. of India, Ministry of Road Transport and Highways, New Delhi
2	Singh, B.N. (Co-convenor)	Additional Director General, Ministry of Road Transport and Highways, New Delhi
3	Sinha, B.K. (Member-Secretary)	Chief Engineer (B) S&R, Ministry of Road Transport & Highways, Transport Bhavan, New Delhi

Members

4	Alam, Pervez	Chief Operating Officer, Hindustan Construction Company Ltd.
5	Arora, D.S.	Jt. Managing Director (Retd.), UP State Bridge Corporation Ltd.
6	Banerjee, A.K.	Member (Technical) (Retd.), National Highway Authority of India
7	Bansal, Shishir	Chief Project Manager, Delhi Tourism, DTTDC Ltd.
8	Basa, Ashok	Managing Director, CEM Consultant (P) Ltd.
9	Bhowmick, Alok	Managing Director, B&S Engineering Consultants Pvt. Ltd., UP
10	Bordoloi, A.C.	Commissioner & Spl. Secretary (Retd.), P.W.B. & N.H. Deptt, PWD Assam
11	Chand, Faqir	Advisor, STUP
12	The CMD, Engg. Proj. (I) Ltd. (Bakshi, S.P.S.)	Engineering Project (India) Ltd., New Delhi
13	The DG, BRO (Shrivastava, Lt. Gen. S.K)	Border Roads Organization, New Delhi
14	The DG, INSDAG (Banerjee, Sushim)	Institute for Steel Development & Growth (INSDAG), Kolkata
15	Dheeraj	Superintending Engineer, Ministry of Road Transport and Highways, New Delhi
16	Dohare, R.D.	Chief Engineer (Retd.), Ministry of Road Transport and Highways, New Delhi
17	The E-in-C, MES (Sharma AVSM, Lt. Gen. Suresh)	Military Engineer Service (MES), New Delhi
18	Ghoshal, A.	Principal Advisor, STUP Consultants (P) Ltd. Kolkata
19	Gupta, Dr. Supratic	Asst. Professor, IIT, New Delhi
20	Heggade, V.N.	Vice President, Gammon Engineers & Contractors (GECPL). Mumbai
21	Khanna, Shobha	Executive Engineer, PWD Ujjain, M.P.
22	Kondai, Bikshapathi	Director General, National Academy of Construction, Hyderabad
23	Kumar, Ashwani	Superintending Engineer, Ministry of Road Transport and Highways, New Delhi
24	Kumar, Satander	Scientist (Retd.), CRRI
25	Pandey, A.K.	Superintending Engineer, Ministry of Road Transport and Highways, New Delhi

26	Pandey, R.K.	Member (Project), National Highway Authority of India, New Delhi
27	Parameswaran, Dr. Lakshmy	Chief Scientist (BAS), Central Road Research Institute, New Delhi
28	Patankar, V.L	DG(RD)&SS (Retd.), Ministry of Road Transport and Highways, New Delhi
29	Pateriya, Dr. I.K.	Director (Technical), National Rural Road Development Agency, New Delhi
30	Puri, S.K.	DG(RD)&SS (Retd.), Ministry of Road Transport and Highways, New Delhi
31	Raina, Dr. V.K.	Consultant, World Bank
32	Raizada, Pratap S.	Senior Vice President, Gammon India Ltd. Mumbai
33	Sharan, G.	DG(RD)&SS (Retd.), Ministry of Road Transport and Highways, New Delhi
34	Sharma, R.S.	Managing Director, M/s STP Ltd., New Delhi
35	Shekhar, Saurav	Director, SA Infra Consultants Pvt. Ltd.
36	Sinha, N.K.	DG(RD)&SS (Retd.), Ministry of Road Transport and Highways, New Delhi
37	Srivastava, A.K.	Chief Engineer, Ministry of Road Transport and Highways, New Delhi
38	Subbarao, Dr. Harshavardhan	Chairman & Managing Director, Construma Consultancy (P) Ltd. Mumbai
39	Tandon, Mahesh Prof.	Managing Director, Tandon Consultants (P) Ltd., New Delhi
40	Verma, G.L.	Managing Director, Engineering & Planning Constructions, New Delhi

Corresponding Members

1	Kand, Sunil C.	Director, C.V Kand Consultant, Bhopal
2	Koshi, Ninan	DG(RD) &SS (Retd.), Ministry of Road Transport and Highways, New Delhi
3	Manjure, P.Y.	Director, Freyssinet Prestressed Concrete Company Ltd (FPCC), Mumbai
4	Reddi, Dr. S.A.	Former JMD GIL
5	The Director, SERC, TN	(Iyer, Prof. Nagesh R)

Ex-Officio Members

President, Indian Roads Congress	(Pradhan, N.K.) E-in-C cum Secretary, Works Department, Odisha
Honorary Treasurer, Indian Roads Congress	(Kumar, Manoj) Director General (Road Development) & Spl. Secretary, Ministry of Road Transport and Highways
Secretary General, Indian Roads Congress	Nirmal, Sanjay Kumar

BACKGROUND

Geophysical techniques are being used worldwide as part of comprehensive geotechnical program. Considering the usefulness of these techniques the Foundation, Sub-Structure Protective Works and Masonry Structure Committee (B-3), IRC felt the necessity to prepare a document, which may provide guidance to the practicing engineers on Geophysical Investigation for Bridges.

The B-3 Committee constituted a sub-committee comprising of the following to draft the document:

Dr. Harshavardhana Subbarao	……..	Convenor
Mr. R. K. Jaigopal	……..	Member
Dr. Sanjay Rana	……..	Member

The sub-committee, deliberated extensively and drafts were presented before the B-3 committee several times. The committee finalised the Draft 'Guidelines on Geophysical Investigation for Bridges" during its meeting held on 23.03.2017.

The draft was considered by the Bridges Specifications and Standards committee (BSS) it its meeting held on 24.06.2017 and approved the document with certain suggestions. The document incorporating the suggestions of BSS committee was placed before the Council in its meeting held on 14.07.2017 at Udaipur. The Council Approved the Document.

The composition of Foundation, Sub-Structure Protective Works and Masonry Structure Committee (B-3) is as given below:

Sharma, R.S.	……..	Convenor
Arora, Daljeet Singh	……..	Co-Convenor
Jain, Sanjay Kumar	……..	Member-Secretary

Members

Bagali, Sharokh	Mahajan, Dr. Ratnakar
Basa, Ashok	Marwah, M.P.
Bongirwar, P.L.	Mhaiskar, Dr. Sharad
Gaharwar, Dr. S.S.	Nayak, Dr. N.V.
Ganguly, Arindom	Parvathareddy, Venkat Mayur B
Huda, Y.S.	Prakash, R.
Jaigopal, R.K.	Rana, Dr. Sanjay
Joglekar, S G	Ray, S.
Kanhere , Dr. D.K.	Saha, Dr. G.P.

1 INTRODUCTION

Geophysical investigations are becoming increasingly acceptable and implemented in the field of geotechnical engineering world over, on account of its simplicity and advantages over traditional methods Geophysical methods can be used to provide volumetric knowledge of unforeseen, highly variable sub-surface ground conditions assisting bridge engineers in pin-point borings, especially in inclined beds for foundations. The geophysical characteristics such as thickness of unconsolidated overburden, bed rock depth, void location, and ground water depth are required in the planning stage itself. Each of these characteristics will significantly affect the design and construction phase of any project. Additional knowledge about these conditions, provided by geophysical methods can reduce project risk, improve construction quality and safety. The document details various geophysical methods, brief principle, operations, capabilities, limitations and method selection criteria. The document also deals with investigation of existing bridges using geophysical methods.

1.1 An Overview of Geophysics

Applied geophysics uses physical methods, such as seismic, gravitational, magnetic, electrical and electromagnetic at the surface of the Earth to measure the physical properties of the subsurface, along with the anomalies in those properties. It has been extensively used, historically, for oil and gas exploration, closely followed by mineral exploration. The depths explored are typically in hundreds and thousands of meters. Engineering geophysics is often used in construction sites to solve a variety of geological, geotechnical, or quality control problems and helps fill gaps in geotechnical data. The basic task of engineering geophysics is to apply physics theories and methods to determine subsurface conditions for building foundations and test quality of man-made structures, like bridges, roads, dams, etc.

Geophysical methods are sensitive to contrast in the physical properties in the subsurface. Different methods respond to different physical properties, like material strength, material conductivity, change in density etc. Geophysical techniques, by virtue of their non-invasive and non-destructive nature, offer an excellent solution for site investigations. No single geophysical technique can uniquely solve the problem due to a large overlapping of physical properties in various subsurface materials. That is the reason why it becomes important to use a combination of geophysical methods to uniquely resolve the problem. Choosing the right tool/technique to address to a specific problem is critical for success of a geophysical program.

1.2 Objectives of Geophysical Investigation

The objectives of Geophysical methods are to locate or to detect the presence of sub-surface structure or bodies and to determine their configuration in terms of size, shape and depth along with physical properties.

Physical properties of sub-surface to be investigated are:

i. Elastic parameters like Young's modulus, bulk modulus, rigidity modulus, Poisson's ratio

ii. Density

iii. Electrical conductivity

iv. Electrical capacitance

v. Electrical inductance

vi. Magnetic susceptibility

vii. Dielectric constant

Application of Geophysical methods to Geotechnical engineering problems by bridge engineers are:

a) Sub-surface characterization for depth of bedrock, type of rock, layers and fractures in rock, grounder water flow, water table, weak zones, expansive clays.

b) Locating buried utilities for constructions of flyovers and subways in urban areas.

c) Locating and shifting of archaeological-interest sites when new developments are taking place.

d) Engineering properties of earth materials like stiffness, density, electrical resistivity, porosity etc.

e) Selecting borehole locations (optimising drilling) and obtain reliable information about the nature and variability of the subsurface between existing boreholes.

f) To obtain subsurface information in environmentally sensitive areas, on contaminated ground, or on private property, where drilling is either not possible or extremely cumbersome.

1.3 Advantages of Geophysical Investigations

Geotechnical geophysical investigations are cost effective and reliable means of imaging the sub-surface between boreholes and below boreholes for determining in-situ properties of soil and rock. These geophysical methods when used for reconnaissance can provide a basis for selection of locations of boreholes. These methods provide a continuous profile of investigated area, eliminating geological surprises otherwise unavoidable if relied only on discrete borehole information as depicted in **Fig.1**.

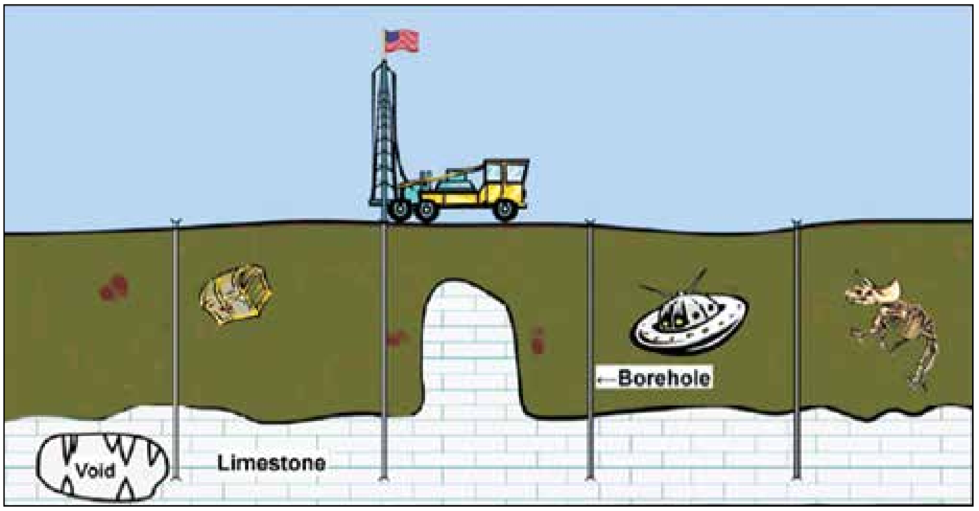


Fig. 1 An isolated geologic structure such as a limestone pinnacle might not be detected by a routine drilling program

Locations where drill rigs cannot be moved like below bridge, steep slopes, marshy lands, deep forests, contaminated sites, heavily congested urban areas, these geophysical methods will come in handy for site investigations. Unlike boring or open excavation, geophysical techniques are non- invasive. Environmentally sensitive locations are ideal for usage of geophysical methods such as contaminated grounds. Geophysical methods are normally considered simple in usage compared to drilling since there are fewer risks associated with utility encounters beneath the surface. Most interesting thing about geophysical methods with respect to geotechnical surveys is that the engineers can optimize or many times reduce the number of boreholes.

Major advantages of engineering geophysics are:

i) Geophysical methods provide continuous profile of sub-surface, as against discrete point information provided by drilling.

ii) It can be used to select borehole locations or can enable engineers to reduce the number of boreholes required.

iii) Variable sub-surface ground conditions such as sudden changes of bedrock profile, fault, fracture zone, boulder, sinkhole, cavity and buried obstruction can be identified which cannot be detected in routine drilling.

iv) It can provide reliable information about the nature and variability of the sub-surface between and below the existing boreholes.

v) Accessibility, portability and non invasiveness.

vi) Required information through borehole survey will not be possible in urban area’s due to limited land accessibility.

vii) Detailed knowledge of unforeseen, variable sub-surface ground condition will reduce project risks and the associated cost.

viii) Other advantages of geotechnical geophysics are related to site accessibility (due to easy portability of instruments), non-invasiveness, and operator safety. These methods can also provide temporal measurements (detecting changes in conditions with time). Geophysical equipments can often be deployed beneath bridges and power lines, in heavily forested areas, at contaminated sites, in urban areas, on steeply dipping slopes, in marshy terrain, on pavement or rock, and in other areas that might not be easily accessible to drill rigs or Cone Penetration Test (CPT) rigs.

ix) Most geophysical tools are non-invasive and, unlike boring or trenching, leave little, if any, imprint on the environment. These considerations can be crucial when working in environmentally sensitive areas, on contaminated ground, or on private property. In addition, geophysical surveys are generally considered less dangerous than drilling since there are fewer risks associated with utility encounters and operations.

However, engineering geophysics is not a substitute for boring and direct physical testing. Rather it complements a well-planned, cost-effective drilling and testing program, and provides a volumetric image of the subsurface rather than a point measurement. Geophysicists refer to borehole information and field geologic maps as ground truth, and rely on ground truth to constrain and verify all geophysical interpretations.

2 SCOPE

The purpose of this document is to provide bridge engineers with a basic knowledge of geophysical methods for solving specific engineering problems during geotechnical site investigation, construction, and maintenance of bridges. The document is intended to provide Engineers with tools that will assist them in the use of suitable geophysical methods to evaluate problems for design, planning, construction, or remediation efforts.

The document provides descriptions of geophysical imaging methods for site investigation for new bridge sites. The document also provides the details of geophysical and non-destructive testing methods for evaluating sub-structure and super structure of existing bridges.

3 GEOPHYSICAL TOOLS

Applied geophysics can be divided into the following seven general methods of exploration:

i) Magnetic
ii) Electrical
iii) Electromagnetic
iv) Seismic
v) Gravitational
vi) Radioactivity and
vii) Well logging

Each geophysical method can be used for many different applications (e.g., mining exploration, oil and gas exploration, engineering, and environmental). The division of each method is based on the physics that governs it; therefore, geophysical techniques (e.g., refraction) within each method (i.e., seismic) are designed primarily for applications of the method to a given problem (e.g., rock quality & depth).

Most of the geophysical methods listed above have corresponding IS, BS or ASTM codes, standardizing their application.

3.1 Geophysical, Non-destructive Testing and Non-contact measuring Tools

Geotechnical geophysical, non-destructive testing and non-contact tools are very similar and in some instances are identical. Physical property models are generated for specific parameters by all these types of instruments.

The major difference between these is that geophysical tools are used to investigate the earth, whereas NDT methods are used to investigate manmade structures like bridges and buildings wherein non-contact tools are used for measuring asphalt temperature, thermal imaging etc without touching the object.

3.2 Geophysical Investigations with Respect to Geotechnical Investigations

Geophysical investigations are carried out preferably prior to geotechnical investigations and are of immense value in selection of borehole locations. Such investigations, in addition, will provide reliable information about variability of sub-surface between two boreholes.

3.3 Selection of Surface Geophysical methods

Selection of most appropriate geophysical method is a two stage process. In stage-1 potentially useful geophysical methods are identified on the basis of engineering problem, which can be done by utilizing the information available on the methods and lateron in stage-II, the most suitable geophysical tools are selected based on the site specific criterion such as depth of target, required resolution, site accessibility and cost.

4 GEOPHYSICAL mETHODS FOR BRIDGE SITE INVESTIGATION

In the process of selecting a site for a bridge, it is necessary to study the requirements of the bridge, volume of traffic, nature and extent of water body system, hydro meteorological factors, maximum flood levels, geological conditions, technical feasibility, seismicity of the region, economic factors etc.

For effective site investigation and characterization few of the obvious geological factors taken into consideration are:

i) The type of the rock and its strength and deformation behaviour i.e. igneous, sedimentary or metamorphic.

ii) Depth of bedrock

iii) Soil profile
iv) Geological discontinuities and associated strength and deformation behaviour i.e., folds, faults, joints and unconformities
v) Groundwater conditions
vi) Squeezing and swelling rock conditions
vii) Running Ground
viii) Gases in rocks
ix) Rock temperature
x) Topographic conditions and structural dispositions

Table 1 provides a comprehensive list of various geophysical methods suitable for various bridge site investigation objectives. These methods are briefly described in this section.

Table 1 Applications for Geophysical Testing methods

Geological Conditions to be Investigated	Useful Geophysical Techniques	
	Surface	**Subsurface**
Stratified rock and soil units (depth and thickness of layers)	Seismic Refraction	Seismic Wave Propagation
Depth to Bedrock	Seismic Refraction, Electrical Resistivity, Ground Penetrating Radar	Seismic Wave Propagation
Depth to Groundwater Table	Seismic Refraction, Electrical Resistivity, Ground Penetrating Radar	
Location of Highly Fractured Rock and/or Fault Zone	Electrical Resistivity	Borehole TV Camera
Bedrock Topography (troughs, pinnacles, fault scarp)	Seismic Refraction, Gravity survey	
Location of Planar Igneous Intrusions	Gravity survey, Magnetics, Seismic Refraction	
Solution Cavities	Electrical Resistivity, Ground Penetrating Radar, Gravity survey	Borehole TV Camera
Isolated Pods of Sand, Gravel, or Organic Material	Electrical Resistivity	Seismic Wave Propagation
Permeable Rock and Soil Units	Electrical Resistivity	Seismic Wave Propagation
Topography of Lake, Bay or River Bottoms	Seismic Reflection (acoustic sounding)	

Geological Conditions to be Investigated	Useful Geophysical Techniques	
	Surface	**Subsurface**
Stratigraphy of Lake, Bay or River Bottom Sediments	Seismic Reflection (acoustic sounding)	
Lateral Changes in Lithology of Rock and Soil Units	Seismic Refraction, Electrical Resistivity	

4.1 Seismic Refraction method

Seismic refraction method is one of the most developed geophysical methods, providing vital information on subsurface which is crucial for most of the engineering projects. The method is covered by IS-15681-2006 “Geological Exploration by Geophysical method- Seismic Refraction- Code of Practice”.

Seismic refraction method is a reliable tool for determining depth of various sub- surface layers, particularly in conjunction with few exploratory borings. The accuracy of depth determination of subsurface interfaces has been improved substantially with the availability of multichannel digital enhancement seismographs and new interpretation techniques, using advanced software & modelling techniques. The method is applicable for investigations on land and underwater as well. **Fig. 2** shows typical layout seismic refraction testing.

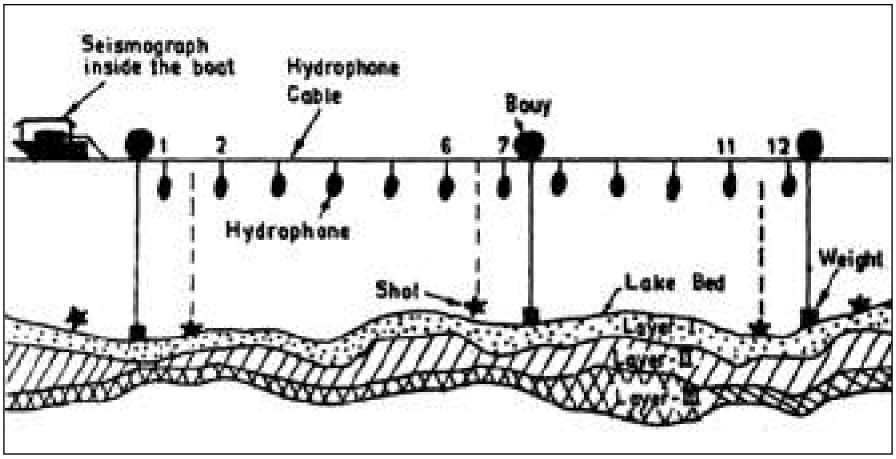


Fig. 2 Typical Layout of Hydrophones for Underwater Seismic Refraction Survey

Seismic refraction surveys being rapid and economical are conducted to aid in selecting a site amongst a number of alternatives at the reconnaissance stage itself. It also forms a part of detailed site investigation at the chosen location. It plays a major role in locating fault and shear zones and in determining engineering parameters like Poison’s ratio, dynamic Young’s modulus, and shear modulus.

This method gives velocity of compressional (P) – waves in sub-surface materials. Although P-waves (compression) velocity can be a good indicator of the type of soil or rock, it is not a unique indicator. **Table 2** shows that each type of sediment or rock has a wide range of seismic velocities and many of these ranges overlap.

Table 2 Range of Velocities for Compressional Waves in Soil and Rock

Sl No.	Natural Soil and Rock	P Wave Velocity m/s
1	Weathered surface material	240 to 610
2	Gravel or dry sand	460 to 915
3	Sand (saturated)	1220 to 1830
4	Clay (saturated)	915 to 2750
5	Water	1430 to 1665
6	Sea water	1460 to 1525
7	Sandstone	1830 to 3960
8	Shale	2750 to 4270
9	Chalk	1830 to 3960
10	Limestone	2135 to 6100
11	Granite	4575 to 5800
12	Basalt	6000 to 6400
13	Quartzite/Phyllitic quartzite	4000 to 6000
14	Quartzite/Phyllitic phyllite	2500 to 3500
15	Gneiss	4000 to 6000

The survey provides sub-surface information over large areas at relatively low cost. It facilitates to identify critical locations for detailed testing by drilling and can readily eliminate less favourable alternative sites. Seismic surveys can also reduce number of boreholes required to test a particular site and improve correlation between boreholes.

4.1.1 *Basic Principle*

Seismic refraction consists of recording the time taken for an artificially provoked surface vibration to propagate through the earth (**Fig.3**). By processing the data recorded at various sensors, absolute velocities, velocity contrasts and the depths of the underlying layers are determined. These results provide information about the nature and thickness of overburden (alluvium deposits), surface of bedrock, the depth of weathering zones in the rock mass, location of geological boundaries and identifies faults or weak zones, scale and width, etc.

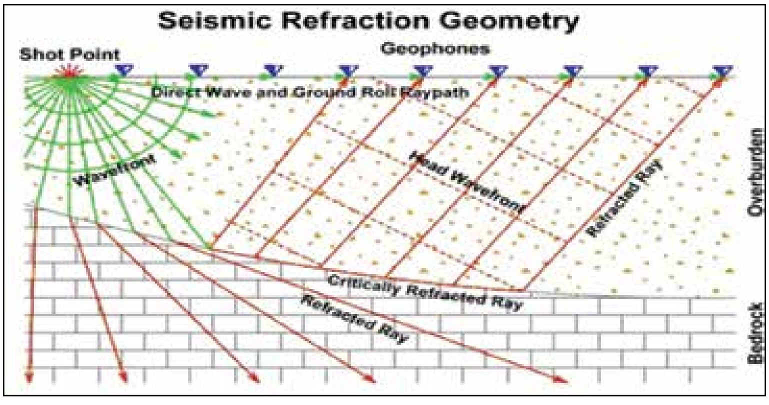


Fig. 3 Basic Principle of Seismic Refraction

The seismic velocities are characteristics of the nature and quality of the bedrock; reduced seismic velocities will characterize a fissured, fractured or sheared rock.

A multi-channel (24-48) engineering seismograph is generally used for the acquisition of greater amount of data per shot (**Figs. 4, 5**). A minimum of seven shot points are used for each spread. These include two far shots on either side of the spread, to provide the true seismic velocity of the sound rock, two end shots to obtain reciprocal times, and three mid shots within the profile to obtain lateral velocity variation in the top layers - overburden.

The length of geophone spread depends upon the required depth of investigation and the dimensions of any subsurface features that are to be mapped. A length of approx. three to four times the depth of investigation is recommended. A geophone spacing of 5 m with 24 channels spread is generally adequate for detailed mapping of subsurface conditions to a depth of approx 30 m. The geophone spacing can be further increased for greater depth of investigation, if required.

Fig. 4 Seismic Refraction Instruments

Fig. 5 Data Collection in Progress

4.1.2 *Key Features of Seismic Refraction*

The Key features of Seismic Refraction method are as follows:

i) Precise determination of soil thickness.
ii) Precise determination of seismic velocities.
iii) Precise determination of water table in overburden.
iv) Localization and identification of geological units.
v) Detailed analysis of soil.
vi) Great accessibility to rough terrain and remote regions.

4.1.3 *Key Applications of Seismic Refraction*

The Seismic Refraction method is useful for the following applications:

i) Determination of bedrock profile, rock quality and depth. Strength of bed rock and weak zones like fractures, shears, weathering and faults for foundation studies.

ii) Estimation of Dynamic Elastic Moduli like Poisson's Ration, Young's Modulus, Shear Modulus.
iii) Location of sinkholes and other manmade objects.
iv) Monitoring of landslides.
v) Thickness of aquifer overlaying impermeable bedrock.
vi) Detection of water table, mainly in alluvial aquifers.
vii) Rippability assessment in mines.
viii) Slope stability studies
ix) Pipeline route studies

4.1.4 *Key Advantages of Seismic Refraction*

The Main advantages of Seismic Refraction method are as follows:

i) Rapid ground coverage.
ii) Only option in rough remote terrains.
iii) Provides continuous profile of subsurface, critical for engineering projects.
iv) Correlation of geological uniformity between boreholes.

4.1.5 *Key Limitations of Seismic Refraction*

This method has the following limitations:

i) Velocity increase with depth is a pre-requisite
ii) Hidden layer and Blind Zone anomalies

4.1.6 *Typical Results of Seismic Refraction*

Figs. 6, 7 and **8** provide examples of results of seismic refraction investigations. Modern processing technique allow for velocity gradient type models wherein velocity increase within a particular soil/ rock unit is also accounted for.

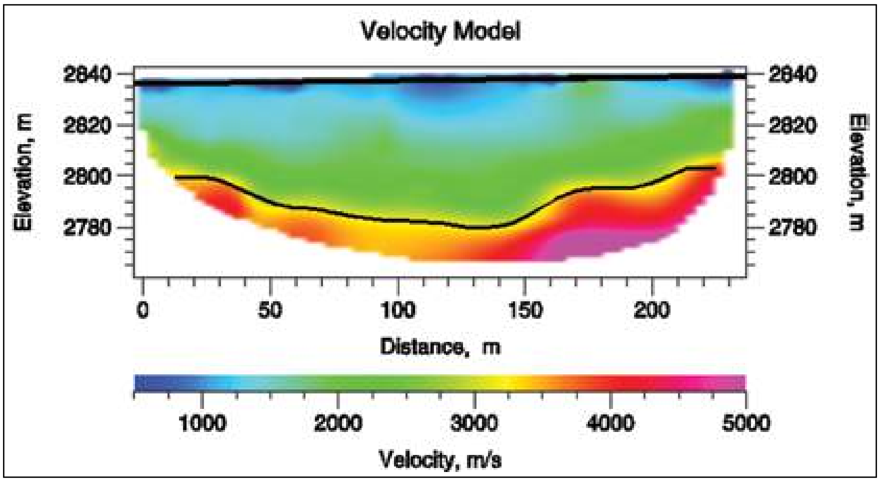


Fig. 6 Typical Velocity model with Rock Interface

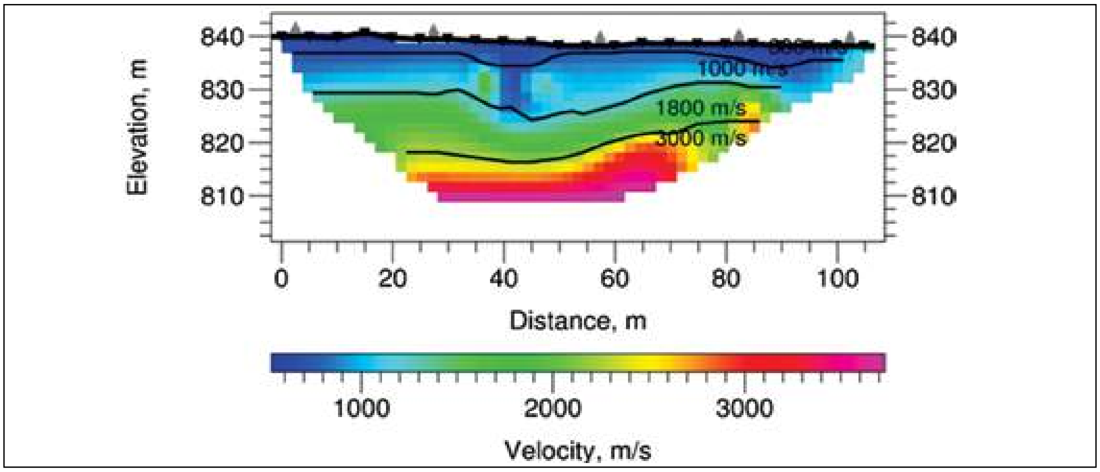


Fig. 7 Typical Velocity model with Various Velocity interfaces

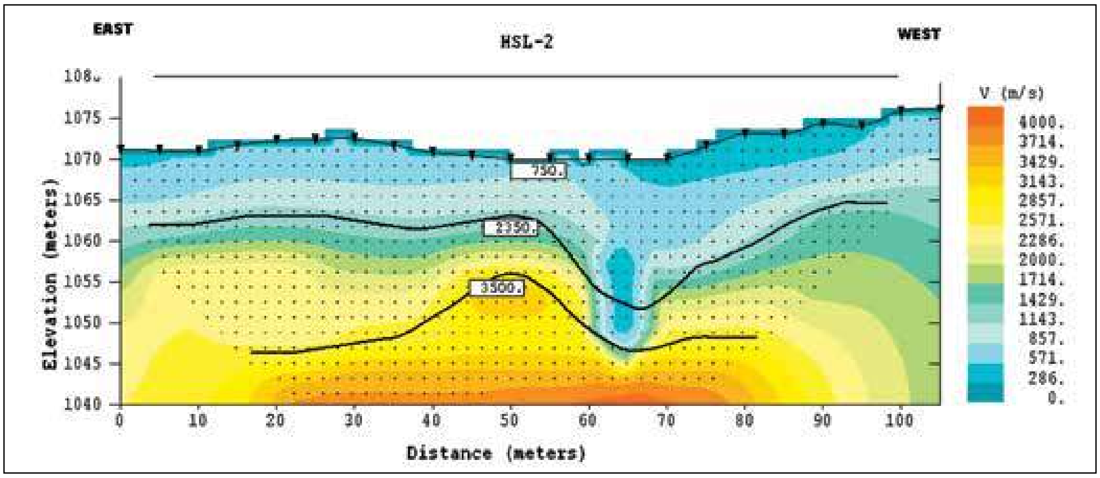


Fig. 8 Typical Velocity model with Detection of Weak Zone

4.1.7 *Equipment for Seismic Refraction*

Equipments used for surface seismic refraction measurement include a seismograph, geophones, hydrophones, geophone cable, hydrophone cable an energy source and a trigger cable or radio link. A wide variety of seismic geophysical equipments are available now (**Fig. 4**).

For engineering geophysics application a 24-48 channel signal enhancement type seismograph is generally used, with 10-14 Hz geophones. Depth investigation upto 30-35 m is generally possible using a 10 kg sledge hammer. For deeper penetration weight drop of explosive source is required.

4.2 Resistivity Imaging method

One of the methods being increasingly used in geological exploration is the electrical resistivity Imaging (also termed as electrical resistivity tomography). The purpose of Electrical resistivity imaging survey is to determine sub-surface resistivity distribution by taking measurements on the ground. From these measurements true resistivity of sub-surface can be estimated. **Fig. 9** provides an example of 2D section derived from electrical resistivity imaging survey.

The resistivity is related to various geological parameters, like, mineral and fluid content, porosity and degree of water saturation in rock. Electrical resistivity surveys have been used for many decades in geotechnical, hydrological and mining investigations. Other applications of electrical resistivity imaging test are:

i. To correlate data from resistivity survey with those obtained from borehole and trial pit logs.

ii. To delineate weak formations, faults and dykes, if any and to identify locations of steeply dipping contacts between different rock types and earth material.

iii. To rapidly explore the sub surface conditions to locate ground water, thickness of over burden, depth of different rock types and stereographic features.

iv. Assessment of ground water potential, quality and determination of aquifer characteristics.

v. To delineate zones of seepage and identify its source around various structures of river valley projects.

vi. For earthing of electrical conductors.

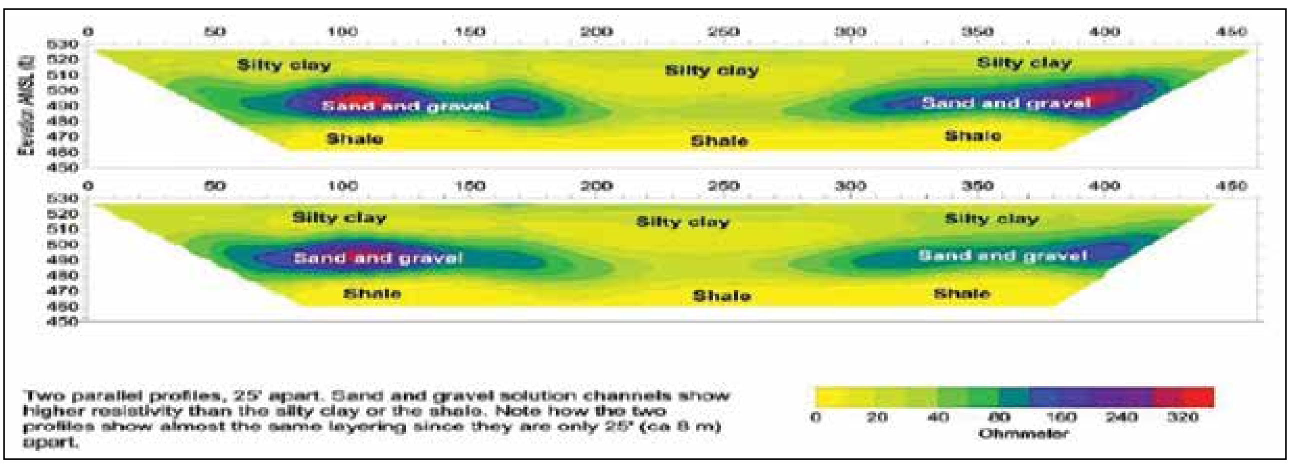


Fig. 9 mapping of stratigraphy in sand and gravel lenses in clay environment

The generally accepted unit of resistivity is Ohm-meter. The resistivity depends on the chemical content of water filling the pore spaces. Salinity of pore water is one of the most critical factors influencing resistivity.

The resistivity's range among rocks and rock materials is very large, extending from 10^{-5} to 10^{15} Ohm-m. Rocks and minerals with resistivity from 10^{-5} to 10^{-1} Ohm-m are considered good conductors. Those having resistivity in the range from 1 to 10^{7} Ohm-m are intermediate conductors and those having resistivity in the range from 10^{8} to 10^{15} Ohm-m are poor conductors. Igneous rocks have the highest resistivity; sedimentary rocks have lowest and metamorphic rocks fall in intermediate zone. The resistivity of particular rock type vary directly with age and lithology, since porosity of rock and salinity of porw water are affected by both of these factors. **Table 3** presents values of resistivity for different rocks, soil and water.

Table 3 Resistivity Values of Some Common materials minerals

material	Resistivity Ohm-m
Igneous and metamorphic Rocks	
Granite	$10^3 – 10^6$
Basalt	103 - 10^6
Slate	$6x10^2$ - $4x10^7$
Marble	10^2 - $2.5x10^8$
Quartzite	10^2 - $2x10^8$
Sedimentary Rocks	
Sandstone	8 - $4x10^3$
Shale	20 - $2x10^3$
Limestone	50 - $4x10^2$
Soils and Waters	
Clay	1 - 100
Alluvium	10-800
Groundwater(fresh)	10 – 100
Sea Water	0.2
minerals	
Galena	$3x10^{-3}$ - $3x10^2$
Bauxite	2 x 10^2-6 x 10^2
Cuprite	10^{-3} - 300
Hematite	3.5 $x10^{-3}$-10^7
Magnetite	5 x 10^{-5} - 5.7 x 10^3
Quartz	4 x 10^{10} – $2x10^{14}$
Uraninite	1 – 200
Calcite	2 x 10^{12}
Rock Salt	30 – 10^{13}
Diamond	10 – 10^{14}

Fig. 10 Resistivity Imaging Instruments

Fig. 11 Data Collection in Progress

4.2.1 *Basic Principle of Electrical Resistivity Imaging*

Measurement of ground resistivity involves passing an electrical current into the ground using a pair of steel or copper electrodes and measuring the resulting potential difference within the subsurface using a second pair of electrodes. These are normally placed between the current electrodes. **Fig. 10** provides a glimpse of resistivity imaging equipment and **Fig. 11** shows a typical field setup for data acquisition. **Fig. 12** shows basic working principle of electrical resistivity imaging with data points corresponding to electrode arrangement.

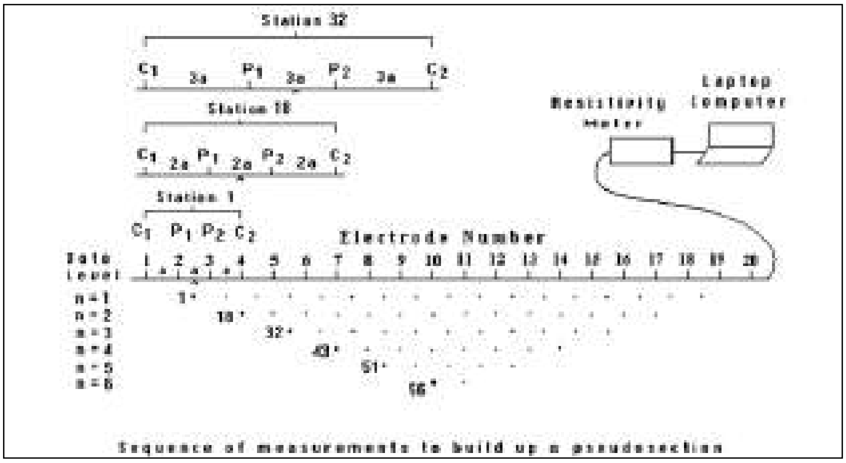


Fig. 12 Arrangement of Electrodes

Unlike conventional resistivity sounding and lateral profiling surveys, 2D resistivity imaging is a fully automated technique that uses a linear array of number of electrodes connected by multicore cable. The current and potential electrode pairs are switched automatically using a laptop computer and control module connected to a ground resistivity meter (that provides the output current).

In this way a profile of resistivity against depth (‘pseudosection’) is built up along the survey line. Data is collected by automatically profiling along the line at different electrode separations. The computer initially keeps the spacing between the electrodes fixed and moves the pairs along the line until the last electrode is reached. The spacing is then increased by the minimum electrode separation (the physical distance between electrodes which remains fixed throughout the survey) and the process is repeated in order to provide an increased depth of investigation.

The maximum depth of investigation is determined by the spacing between the electrodes and the number of electrodes in the array. For a 64 electrode array with an electrode spacing of 5 m this depth is approximately 60 m. However, as the spacing between the active electrodes is increased, fewer and fewer points are collected at each ‘depth level’, until on the final level only 1 reading is acquired (**Fig. 13**). In order to overcome this, the array is ‘rolled-along’ the line of investigation in order to build up a longer pseudo section.

The raw data is initially converted to apparent resistivity values using a geometric factor that is determined by the type of electrode configuration used. Many 2D resistivity imaging surveys are carried out using the Wenner Array. In this configuration the spacing between each electrodes is identical. Once converted the data is modelled using finite element and least squares inversion methods in order to calculate a true resistivity versus depth pseudo section.

4.2.2 *Key Applications of Electrical Resistivity Imaging*

Key applications of electrical resistivity imaging are as follows:

i) To determine the underground water resources
ii) To determine bedrock quality and depth measurements
iii) Mineral prospecting
iv) Dam structure analysis
v) To determine landfill characteristics
vi) Contamination source detection

4.2.3 *Key Advantages of Electrical Resistivity Imaging*

Main advantages of electrical resistivity imaging are as follows:

i) Excellent 2-dimensional display of ground resistivity.
ii) Delineation of small features like cavity, contamination plumes, weak zones in structures like dams etc.
iii) The technique is extremely useful for investigations of important sites to get information on weak zones or buried channels, under the rock interface, which goes undetected in seismic refraction, which terminated at rock interface.
iv) Resistivity imaging can also be effectively used to determine rock profile along bridge axis across high current shallow rivers where deployment of hydrophones is not possible restricting use of seismic refraction (**Figs. 14,15**).
v) For deep penetration seismic refraction techniques requires use of explosives, which are not always feasible to deploy especially in sensitive areas. In such cases resistivity imaging can be effectively used to get detailed information of deeper layers (Fig. 13).

4.2.4 *Examples of Results of Electrical Resistivity Imaging*

Figs. 13, 14 and **15** show few examples of resistivity imaging survey for different applications, covering land as well as under water application of the technique. The example demonstrates that resistivity imaging can be used effectively to detect features like cavities in rocks, weak zones, fractures etc. The results of electrical imaging are 2D sections of resistivity along the survey line providing fine details of subsurface.

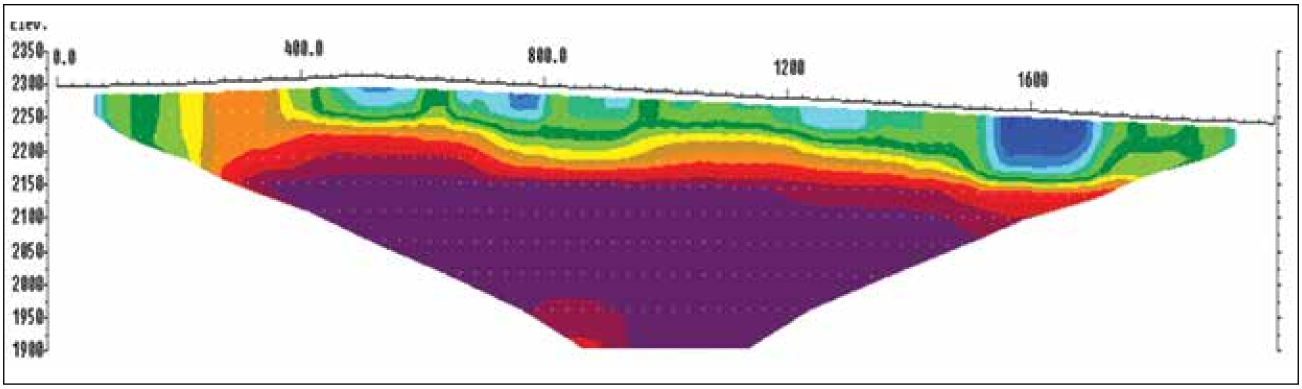


Fig. 13 Typical Resistivity Section for Bedrock Detection (Depth- 400 m)

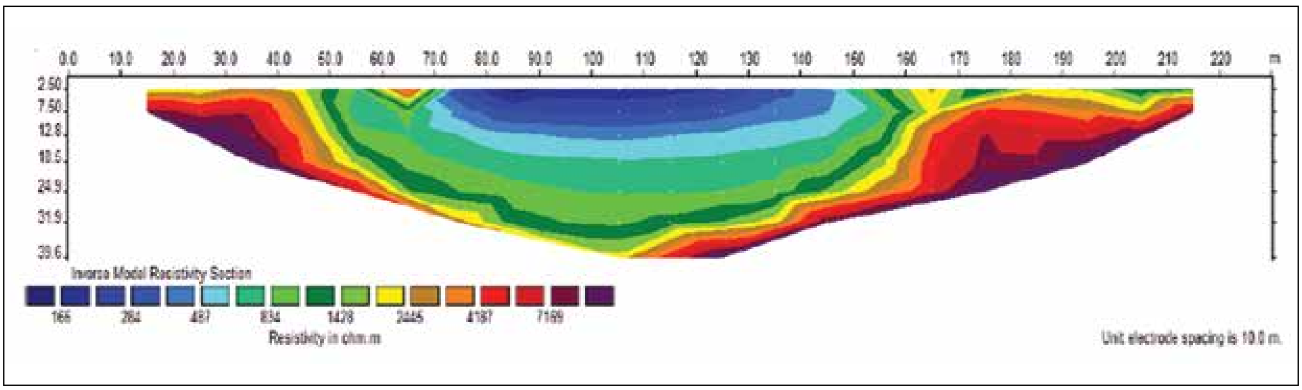


Fig. 14 Section Across Bridge Axis in Flowing River (Yellow line represents rock interface)

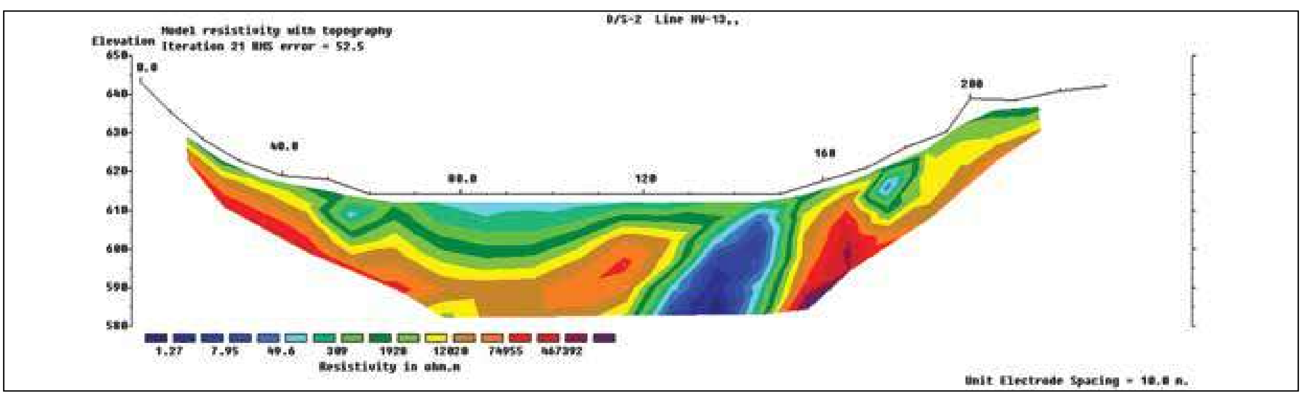


Fig. 15 Section Across Bridge Axis in Flowing River (Blue- Shear Zone Detected)

4.2.5 *3-D Resistivity Imaging Surveys*

All geological structures are three dimensional in nature, hence a 3-D resistivity survey using 3-D interpretation model gives the most accurate result. With the development of multi channel resistivity meters which enables recording of more than one measurement at a time and availability of computers the inversion of very large data sets comprising more than 8000 data points and survey grid of greater than 30 m x 30 m can be enabled. The pole-pole, pole- dipole and dipole-dipole arrays are frequently used for 3-D surveys because other arrays have poor data coverage near the edge of survey grid. **Fig. 16** is an example of a slice from a 3D model, from a work carried out for cavity detection in sandstone at pier location of a bridge.

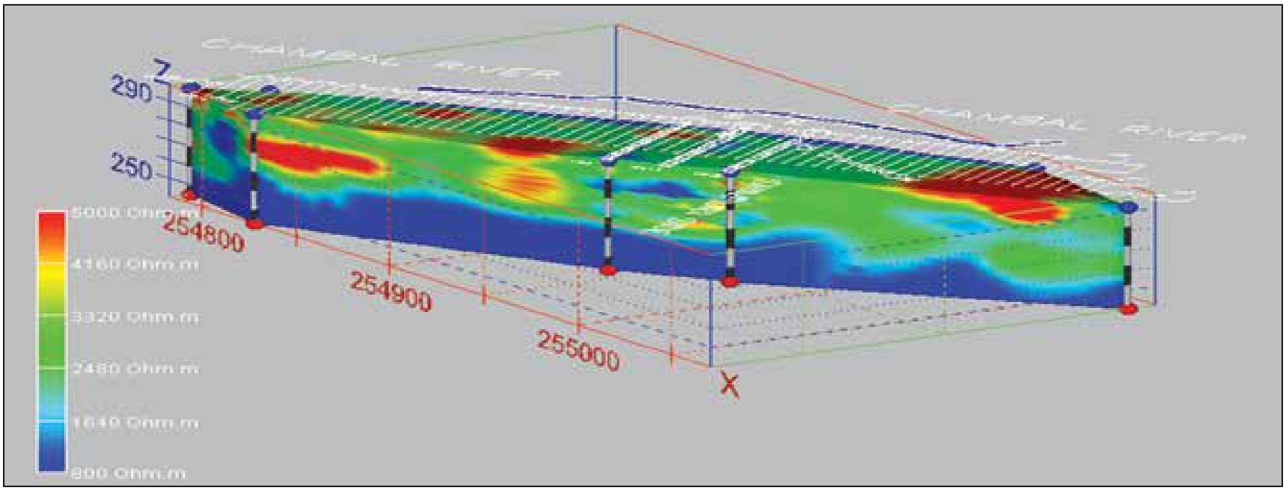


Fig. 16-3D Resistivity Interpretation model

4.3 Remi - Refraction micro-Tremor method

ReMi can be performed under the same layout as used for seismic refraction, to obtain excellent shear wave velocity profiles of subsurface.

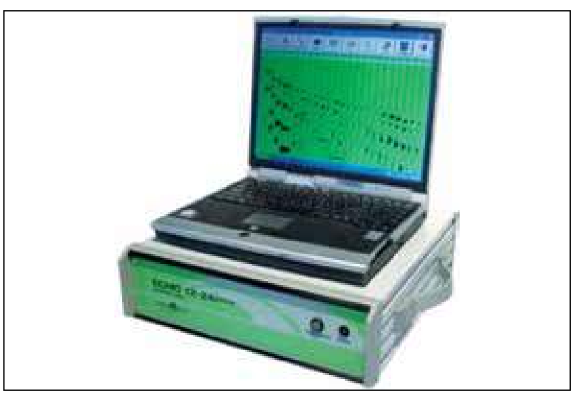
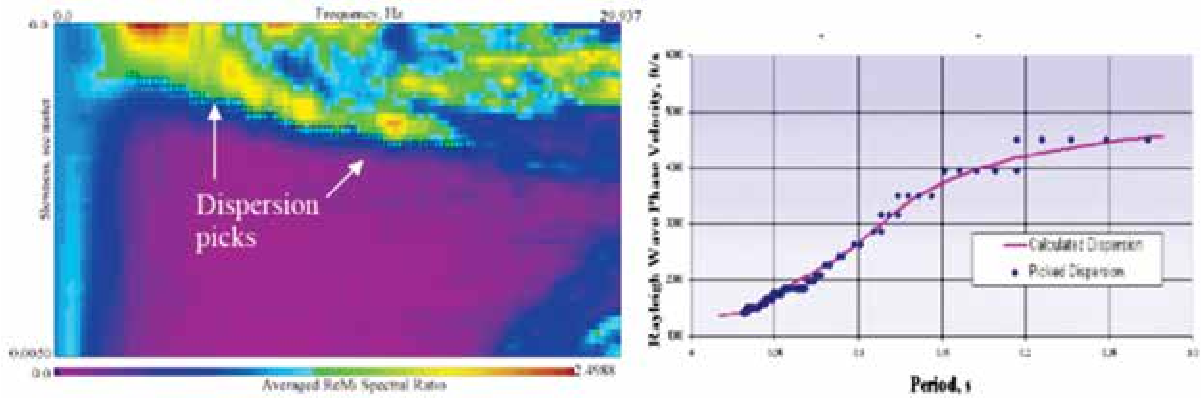


Fig. 17 Remi Seismograph

Fig. 18 Data collection in progress

ReMi is a new, proven seismic method for measuring in-situ shear-wave (S-wave) velocity profiles. It is economic both in terms of cost and time. Testing is performed at the surface using the same conventional seismograph and vertical P-wave geophones used for refraction studies (**Figs. 17,18**). The seismic source consists of ambient seismic “noise”, or micro-tremors, which are constantly being generated by cultural and natural noise. Because conventional seismic equipment is used to record data, and ambient noise is used as a seismic source, the ReMi method is less costly, faster and more convenient than borehole methods and other surface seismic methods, such as SASW and MASW used to determine shear-wave profiles. Depending on the material properties of the subsurface, ReMi can determine shear wave velocities down to a minimum of 40 m and a maximum of 100 m depth.



Shear-wave dispersion curve derived from ambient seismic noise, shown on the left, is picked and modeled (right panel)

Fig. 19 Shear-Wave Dispersion Curve Derived from Ambient Seismic Noise

4.3.1 *Procedure for ReMi*

The data acquisition procedure consists of obtaining five to ten 20-second seismic noise records using conventional seismograph and P-wave geophones. The wave field transformation of the noise record reveals the shear-wave dispersion curve (**Fig. 19**). The shear-wave dispersion curve from the wave field transformation is then manually picked and the picks modelled to determine the subsurface shear-wave velocity profile (**Fig. 20**). During data analysis, the wave field from the three separate noise records are manually picked and modelled for the purpose of quality control. The resolution of the final model is quantified based on the uncertainty in the picks.

The data is recorded using natural noise, by making people run along the seismic profiles, by making people jump at various points of the profile, by tapping of hammer at one end of the profile etc. The effort is to generate as much as random noise as possible in various ways.

4.3.2 *Key Applications of ReMi*

ReMi can be used to obtain Shear wave velocity (Vs) profiles for:

- i) Earthquake site response
- ii) Liquefaction analysis
- iii) Soil compaction control
- iv) Mapping the subsurface and estimating the strength of subsurface materials
- v) Finding buried cultural features such as dumps and piers

4.3.3 *Key Advantages of ReMi*

The ReMi method has several advantages in contrast to the borehole measurements. ReMi tests a much larger volume of the subsurface. The results represent the average shear wave velocity over distances as large as 200 m. Because ReMi is non-invasive and non-destructive in nature, and uses only ambient noise as a seismic source, no permissions are required for its use. ReMi seismic lines can be deployed within the road medians, at active construction sites, or along highways, without affecting the ongoing work or traffic flow. Unlike other seismic methods for determining shear wave velocity, ReMi uses the ongoing activities as seismic sources. A ReMi survey usually takes less than two hours, from setup through breakdown. These advantages sum to substantial savings in time and cost. Moreover the method provides more accurate results compared to the conventional effort of picking up shear waves from records which more often than not lead to errors.

4.3.4 *Example Result of ReMi*

Fig. 20 presents typical result obtained from ReMi survey, showing shear wave velocities upto a depth of 100 m.

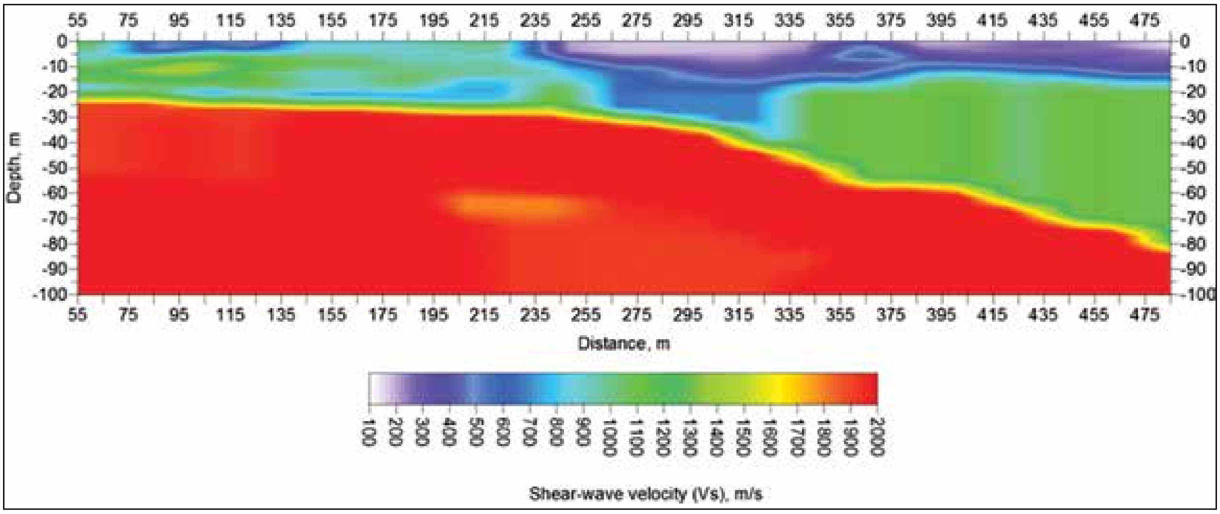


Fig. 20 Remi Section showing Bedrock (Red Layer) and Weak Zone (Blue Zone in Green Zone)

4.4 Crosshole/ Downhole/ Uphole Surveys

The primary purpose of obtaining crosshole data is to obtain the most detailed in situ seismic wave velocity profile for site-specific investigations and material Characterization. Crosshole velocity data are valuable for assessing man-made materials, soil deposits, or rock formations. **Figs. 21, 22, 23** and **24** provide instruments and arrangement for Crosshole surveys.

The seismic technique determines the compressional (P) and/or shear (S) wave velocity of materials at depths of engineering and environmental concern where the data can be used in problems related to soil mechanics, rock mechanics, foundation studies, and earthquake engineering. Crosshole geophysical testing is generally conducted in the near surface (upper hundred meters) for site-specific engineering applications. All the dynamic elastic moduli of a material can be determined from knowledge of the in situ density, P, and S-wave velocity. Since procedures to determine material densities are standardized, acquiring detailed seismic data yields the required information to analytically assess a site. Low-strain material damping and inelastic attenuation values can also be obtained from the crosshole surveys. However, the most robust application of crosshole testing is the ability to define in situ shear-wave velocity profiles for engineering investigations associated with earthquake engineering.

Fig. 21 Crosshole Seismic Borehole Sensor

Fig. 22 Data Collector

The objective of acquiring crosshole data can be multipurpose; i.e. the seismic velocity results obtained may be used for evaluation of lateral and vertical material continuity, liquefaction analyses, deformation studies, or investigations concerning amplification or attenuation of strong ground motion. Typically, the crosshole surveys are geophysical tools for performing explorations during the phase two field investigations (wherein phase one field investigations include surface geophysical surveys, follow-up drilling, trenching, and sampling of the in situ materials). During phase two field exploration, the information gathered is more critical to the analytical site-specific Characterization. Although both phase one and phase two results are important, the two independent sets of data must be integrated in the final analysis.

Crosshole techniques are most useful when phase one site explorations indicate horizontal and particularly vertical variability of material properties. When layers of alternating density or stiffness are either known to exist or are encountered during phase one field investigations, crosshole seismic tests are recommended to define the in situ velocities within each layer. Acquiring crosshole seismic data resolves hidden layer velocity anomalies that cannot be detected with conventional surface methods, allows both final interpretation of other surface geophysical data (seismic or electrical), and permits both empirical and theoretical correlation with other geotechnical material parameters.

In order to have quantitative and quality assured results, crosshole tests performed for either engineering or environmental problems should be conducted in accordance with procedures established. Crosshole seismic test procedures are outlined in ASTM test designation D4428 M-84 (1984). Crosshole geophysical surveys have become more widely used and accepted for engineering as well as environmental applications. Coupling detailed site information obtained from the crosshole tests with the overall acceptance of the validity of the velocity data, these standards use both empirical correlations for liquefaction and specific input parameters for deformation or ground motion analyses.

4.4.1 *Basic Theory of Crosshole Seismic*

Crosshole testing takes advantage of generating and recording (seismic) body waves, both the P- and S waves, at selected depth intervals where the source and receiver(s) are maintained at equal elevations for each measurement. **Fig. 23** illustrates a general field setup for the crosshole seismic test method. Using source-receiver systems with preferential orientations in tandem (i.e., axial orientations, which complement the generated and received wave type/signal) allows maximum efficiency for measurement of in situ P- or S-wave velocity depending on the axial orientation. Due to the different particle motions along the seismic ray path, it is crucial to use optimal source-receiver systems in order to have best record of crosshole P- or S-waves. Because only body waves are generated in the source borehole during crosshole tests, surface waves (ground roll) are not generated and do not interfere with the recorded body-wave seismic signals.

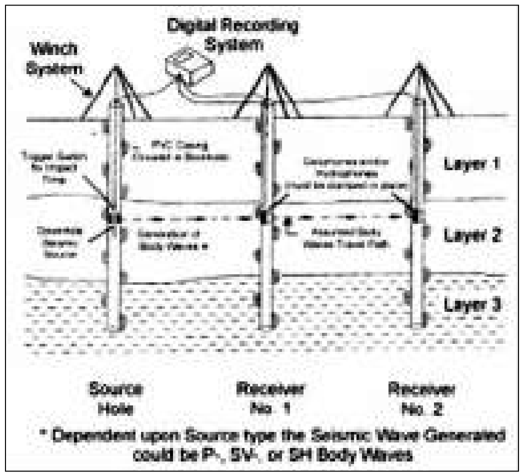


Fig. 23 Schematic Arrangement for Crosshole method

Particle motions generated with different seismic source types used during crosshole testing are three-directional. Therefore, three-component geophones with orthogonal orientations yield optimal results when acquiring crosshole P- and/or S-wave seismic signals. With three-component geophones, there is one vertically oriented geophone and two horizontal geophones. For crosshole tests, one horizontal geophone remains oriented parallel to the axis between the boreholes (radial orientation), and the other one remains oriented perpendicular to the borehole axis (transverse orientation). In this case, the two horizontal axis geophones must remain oriented, radially and transversely, throughout the survey. This is accomplished with loading poles or with geophones that can be electronically oriented.

P-waves are generated with a sparker or small explosive device (one that will not damage the PVC casing) such that along the assumed straight-ray propagation path the seismic impulse compresses and rarefies the materials radially toward the receiver borehole(s). Experience has proven that for optimal measurement of the P-wave signal, a hydrophone has the greatest pressure-pulse sensitivity for compressional-wave energy. Also, hydrophones do not need to be clamped against the borehole wall; however, water must be present in the receiver borehole in order to couple the hydrophone to the casing/formation.

For either surface or crosshole seismic testing in unconsolidated materials, P-wave velocity measurements are greatly affected by the moisture content or percent saturation. In crosshole testing, the seismic measurements encroach closer to the water surface with each successive depth interval. As the vadose zone and water surface are encountered, P-wave velocities become dependent upon the percent saturation, and the Poisson’s ratio is no longer a valid representation of the formation characteristics e.g., Poisson’s ratio increases to 0.48-0.49

in 100% saturated soils. Hence, below the water surface, the P-wave is commonly termed as the fluid wave, because its propagation velocity is governed by the pore fluid(s), not by the formation density. Fluid-wave velocities in fresh water range from 1,400 to 1,700 m/s, depending upon water temperature and salt content.

S-waves generated in crosshole testing may be split into two wave types, each with different particle motions--SV- and SH-waves, vertical or horizontal particle motions, respectively. Shear waves have the unique capability of polarization, which means that impacting the material to be tested in two directions (up or down, left or right) yields S-wave signals that are 180° out of phase. A seismic source with reversible impact directions is the key factor for quality crosshole S-wave data acquisition and interpretation. **Fig. 24** shows a series of crosshole SV-waves with reversed polarity (note the low amplitude of the P-wave energy as compared to the S-wave energy) received at both the receiver boreholes.

Typically, the S-wave generated in most crosshole testing is the SV-wave, which is a vertically polarized horizontally propagating shear wave. That is, the ray path is horizontal but the (shear) particle motion along the ray path is in the vertical plane. These SV-waves are easiest to generate because of commercially available borehole impact hammers that have reversible impact directions (up or down), and they are also the easiest to record because only one vertically oriented geophone is required in each receiver borehole. Alternatively, SH-waves can be generated and recorded in crosshole testing. SH-waves also propagate horizontally, but their (shear) particle motion is in the horizontal plane (i.e., horizontally polarized horizontally propagating S-waves). Therefore, in order to generate and record SH-wave signals, horizontal impacts and geophones are required; also, the orientation of the source and receiver must be parallel while their respective orientation remains perpendicular to the axis of the boreholes (transverse orientation).

Theoretically, there is no difference in the body wave velocity for SV- and SH-waves, which justifies use of the uncomplicated vertical source for generation of SV-waves, and vertically oriented geophones for signal detection. There are studies, however, which indicate significant velocity dependence of the SV- and SH-waves due to anisotropic states of stress in either the horizontal or vertical stress field (particularly in soil deposits or fractured rock formations.

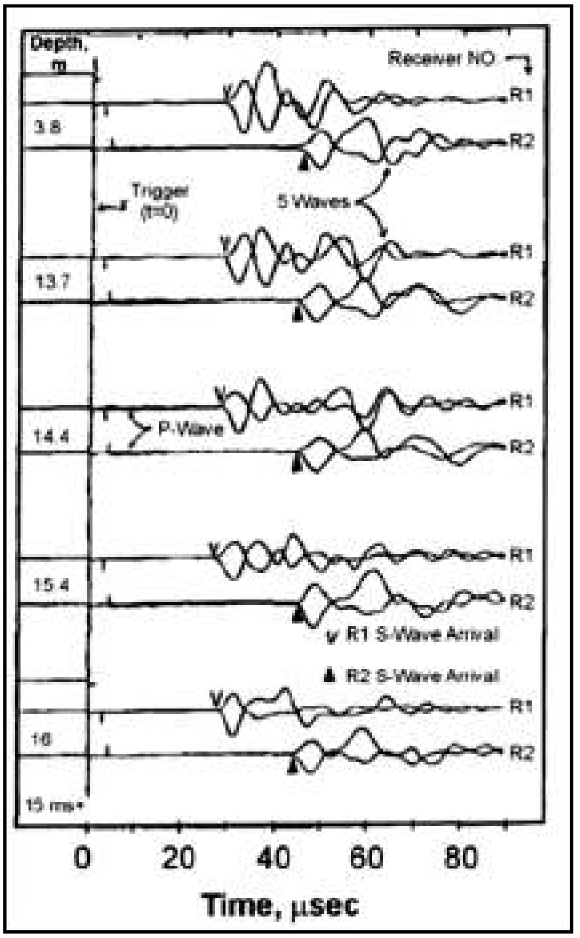


Fig 24 Crosshole SV-Wave Paired Borehole Records at Five Depths

The requirement for multiple drill holes in crosshole testing means that care must be taken when completing each borehole with casing and grout. Normal procedures call for PVC casing and a grout mix that closely matches the formation density. Success of crosshole seismic testing depends primarily on borehole preparation and completion procedures. Poor coupling between the casing and the formation yields delayed arrival times and attenuated signal amplitudes, particularly for (higher frequency) P-waves. Matching the formation density with a grout mix is not very difficult, but in open coarse-grained soils, problems may arise during grout completion with losses into the formation. Even small grout takes may affect the velocity measured between two closely spaced drill holes. Several techniques to plug the porosity of the surrounding formation are available (e.g., cotton-seed hulls, crushed walnut shells, or increased bentonite concentration in the grout mix). It should be recognized that increasing the ratio of bentonite/cement within the grout mix does affect density, but so long as the mix sets and hardens between the casing and in situ formation, quality crosshole seismic signals can be obtained.

Another critical element of crosshole testing, which is often ignored, is the requirement for borehole directional surveys. There are several very good directional survey tools available that yield detailed deviation logs of each borehole used at a crosshole site. Borehole verticality and direction (azimuth) measurements should be performed at every depth interval wherein seismic data are acquired. With the deviation logs, corrected crosshole distances between each borehole may be computed and used in the velocity analysis. Since seismic wave travel times should be measured to the nearest tenth of a millisecond, relative borehole positions should be known with centimetre accuracy. Assuming that the boreholes are vertical and plumb based verticality checks leads to computational inaccuracies and ultimately to data that cannot be quality assured.

4.4.2 *Data Acquisition of Crosshole Seismic*

Recording instruments used in crosshole testing vary considerably, but there are no standard requirements other than exact synchronization of the source pulse and instrument trigger for each recording. Crosshole measurements rely considerably on the premise that the trigger time is precisely known as well as recorded. The recorded trigger signal from zero-time geophones or accelerometers mounted on the downhole impact hammer allows accurate timing for the first arrival at each drill hole. This becomes uniquely critical when only two drill holes are used (i.e., source and one receiver) because there is no capability of using interval travel times; in this case, the velocity is simply determined through distance traveled divided by direct travel time. Utilizing digital recording equipment affords the operator the ability to store the data on magnetic media for analysis at a later date; but more importantly, digital data can be filtered, smoothed, and time-shifted during analysis. Also, digital signal processing may be directly performed for coherence, frequency-dependent attenuation, and spectral analysis.

Numerous studies have shown that the effects on crosshole measurements by the choice of geophone are not critical to the results. There are only two requirements for the receivers: the receiver (velocity transducer) must have a flat or uniform output response over the frequency range of crosshole seismic waves (25 to 300 Hz); and, a clamping device must force the receiver against the borehole wall such that it is not free-hanging. The clamping device should not affect the mechanical response of the geophone (i.e., resonance), nor should the uphole signal wire. If an SH-wave source is selected, then horizontal geophones must be used and oriented as previously described to detect the SH-wave arrivals. It is paramount that the polarity of each geophone be known prior to data acquisition because the direct arrivals of S-waves with reversed polarity can be easily misinterpreted.

4.4.3 *Key Feature of Crosshole Seismic*

The key feature of Crosshole Seismic method is Precise determination of P and S wave seismic velocities.

4.4.4 *Key Advantages of Crosshole Seismic*

Main advantages of Crosshole Seismic method are:

i) Determination of Dynamic Elastic Moduli like Young's Modulus, Shear Modulus and Poisson's Ratio.

ii) Detects even thin anomalous zones in subsurface.

4.4.5 *Key Limitations of Crosshole Seismic*

The Crosshole Seismic Method has following limitations:

i) Good borehole preparation is critical

ii) Borehole verticality/ inclination to be ascertained.

Downhole and Uphole surveys also work on the similar principle as explained in this section, with minor differences in data acquisition methodology.

4.5 Seismic Reflection Method

Deep seismic reflection surveying is the most advanced technique in geophysics nowadays, due to its application on a huge scale for oil and gas exploration. This technique does, however, have other applications on a smaller scale, such as for civil engineering project site investigation. The methodology is identical, but the equipment and parameters are adjusted to provide a higher resolution at shallow depths. **Fig. 25** presents basic principle and geometry of seismic reflection survey.

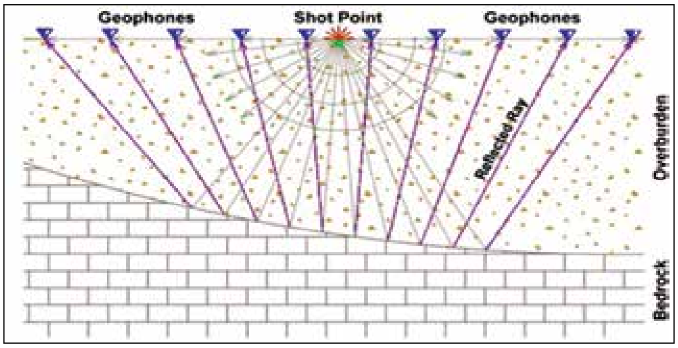


Fig. 25 Seismic Reflection Geometry

Seismic energy is generated at the surface using either impulsive sources (dynamite) or continuous sources (Vibroseis). The returned energy is recorded by a series of geophones installed along lines at the surface. Reflection of the energy is caused by contrasts in acoustic impedance between the various strata. Data processing is a complex sequence of operations carried out usually on powerful computers using specialized software. The final product is a 2-D or 3-D dataset of seismic reflectors, which can then be correlated to specific geological interfaces through the use of borehole information.

Seismic reflection uses field equipment similar to seismic refraction, but field and data processing procedures are employed to maximize the energy reflected along near vertical ray paths by subsurface density contrasts. Reflected seismic energy is never a first arrival, and therefore must be identified in a generally complex set of overlapping seismic arrivals - generally by collecting and filtering multi-fold or highly redundant data from numerous shot points per geophone placement. Therefore, the field and processing time for a given lineal footage of seismic reflection survey are much greater than for seismic refraction. However, seismic reflection can be performed in the presence of low velocity zones or velocity inversions, generally has lateral resolution vastly superior to seismic refraction, and can delineate very deep density contrasts with much less shot energy and shorter line lengths than would be required for a comparable refraction survey depth.

The main limitations to seismic reflection are its higher cost than refraction (for sites where either technique could be applied), and its practical limitation to depths generally greater than approximately 15 m. At depths less than approximately 15 m, reflections from subsurface density contrasts arrive at geophones at nearly the same time as the much higher amplitude ground roll (surface waves) and air blast (i.e. the sound of the shot). Reflections from greater depths arrive at geophones after the ground roll and air blasts have passed, making these deeper targets easier to detect and delineate.

In hydropower projects the seismic reflection method can detect geologic structures in fault zones, find shallow, soft layers of underground earth materials, reduce mapping uncertainties and can greatly reduce the investigation costs of engineering projects.

4.5.1 *Key Applications of Seismic Reflection*

Key applications of Seismic Reflection method are as follows:

i) Oil and gas exploration
ii) Geological mapping studies
iii) Mineral exploration
iv) Civil engineering site investigations

4.5.2 *Example Results of Seismic Reflection*

Figs. 26, 27 and **28** are few typical examples of geological interpretation based on seismic reflection data.

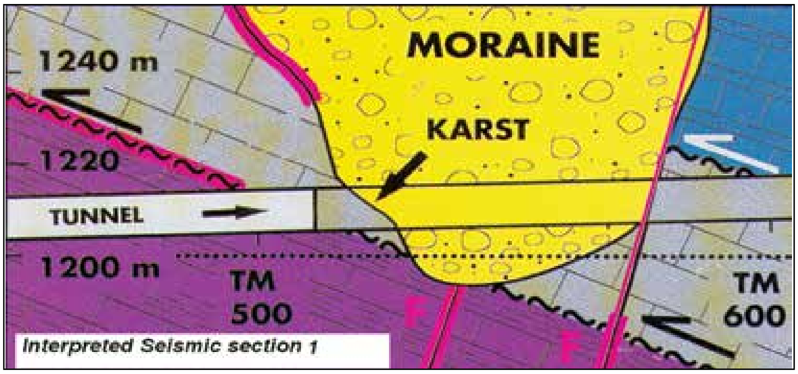


Fig. 26 Geological Interpretation Based on Seismic Reflection Data

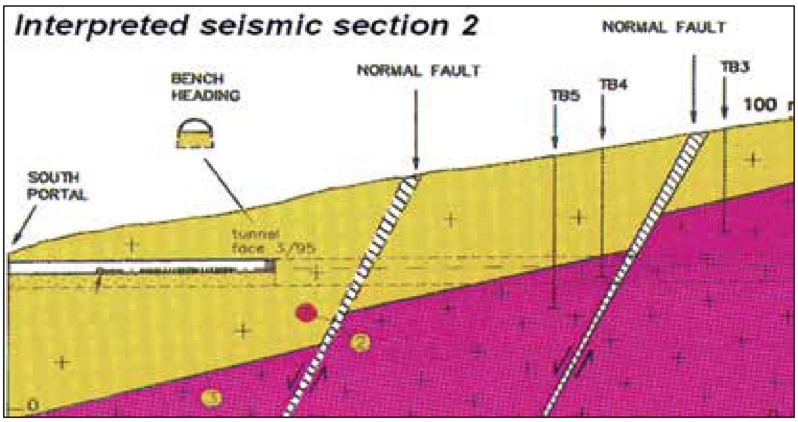


Fig. 27 Geological Interpretation Based on Seismic Reflection Data

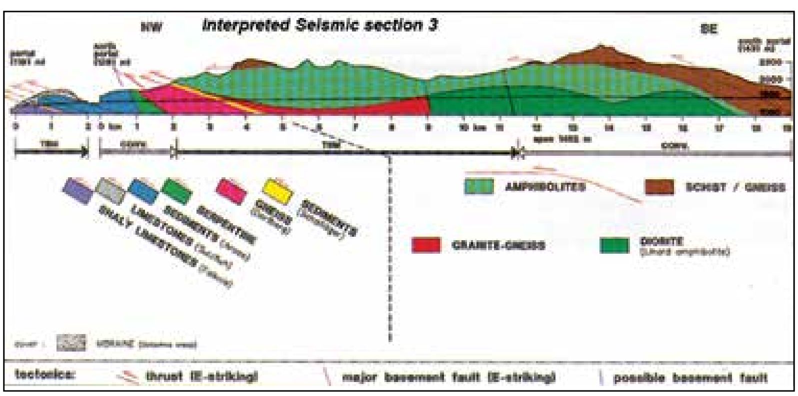


Fig. 28 Geological Interpretation Based on Seismic Reflection Data

4.6 Ground Penetrating Radar method

Ground Penetrating Radar, also known as GPR, Georadar, Subsurface Interface Radar, Geoprobing Radar, is a totally non-destructive technique to produce a cross section profile of subsurface without any drilling, trenching or ground disturbances. Ground Penetrating Radar (GPR) profiles are used for evaluating the location and depth of buried objects and to investigate the presence and continuity of natural subsurface conditions and features. GPR instruments and survey details are in **Figs. 29, 30** and **31**.

Fig. 29 GPR Investigation in Progress

Fig. 30 Ground Penetrating Radar

The GPR operates by transmitting electromagnetic impulses into the ground through transmitter antenna. The transmitted energy is reflected from various buried objects or distinct contacts between different earth materials, across which there is a contrast in dielectric constant. The antenna then receives the reflected waves and displays them in real time on screen. Data is also saved in appropriate memory for later processing and interpretation.

Ground penetrating radar waves can reach depths upto 60 m in low conductivity materials such as dry sand or granite. Clays, shale and other high conductivity materials may attenuate or absorb GPR signals, greatly decreasing the depth of penetration.

The depth of penetrating in also determined by the GPR antenna used. Antennas with low frequency obtain reflections from deeper depths but have low resolution. These low frequency antennas are used for investigating the geology of a site, such as for locating sinkholes or fractures, and to locate large, deep buried objects.

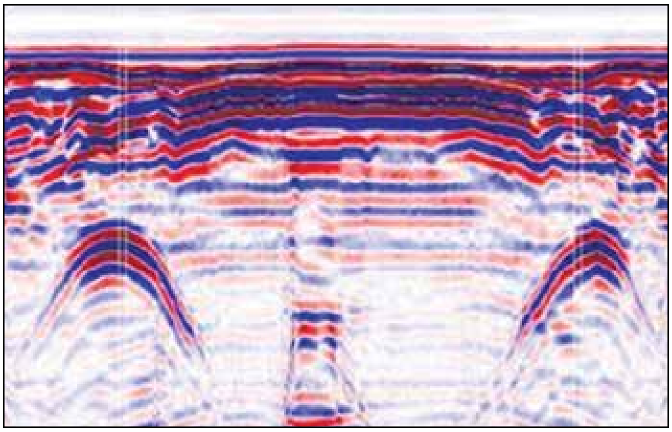


Fig. 31 Radargram from GPR Survey

Antennas with higher frequencies (300 to 2000 MHz) obtain reflections from shallow depths (0 to 10 meters) and have a high resolution. These high frequency antennas are used to investigate surface soils and to locate small or large shallow buried objects, pipes, cables and rebar in concrete.

GPR can detect objects of any material, metallic or non-metallic.

4.6.1 *Key Application Areas of GPR*

Key appications of GPR are:

i) Geological and hydro-geological investigations including mapping of bedrock topography, water levels, solution features, glacial structures, soils and aggregates.

ii) Engineering investigations to evaluate dams, sea walls, tunnels, pavements, roadbeds, railway embankments, piles, bridge decks, river scour, buildings and monuments.

iii) Location and evaluation of buried structures including utilities, foundations, reinforcing bars, cavities, tombs, archaeological artifacts, and animal burrows.

iv) Site investigations: location of buried engineering structures and underground storage tanks.

v) Subsurface mapping for cables, pipes and other buried structures prior to trench-less operations.

4.6.2 *Key Advantages of GPR*

Main advantages of GPR technique are:

i) Rapid ground coverage- Antenna towed either by hand or from a vehicle.

ii) High-resolution coverage of the survey area, detecting even small objects.

iii) On-site interpretation possible due to instant graphic display.

4.6.3 *Key Limitations of GPR*

GPR technique has following limitations:

i) Data acquisition may be slow over difficult terrain.

ii) Depth of penetration is limited in materials with high electrical conductivities, clays.

iii) Energy may be reflected and recorded from above ground features, walls, canopies, unless antennae are well shielded.

iv) Artifacts in the near surface (reinforcing bars, boulders, components of made ground) may scatter the transmitted energy and complicate the received signal and/or reduce depth of penetration.

v) Working on principle of reflection, GPR detects the utilities and provides information on depth and location. Classification of utility any further can be done only with availability of background data and is not a deliverable of GPR survey.

4.6.4 *Examples of Results of GPR*

Few examples from various application areas are presented in **Figs. 32 to 44**:

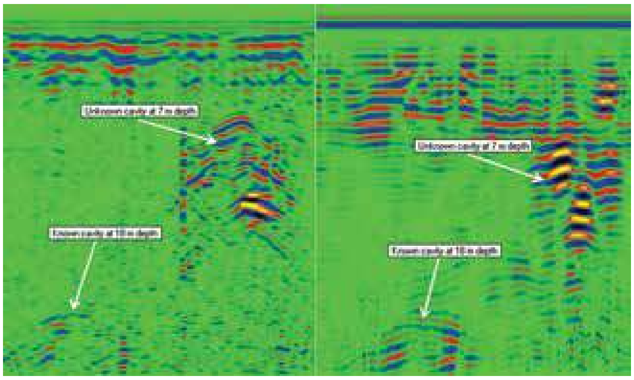


Fig. 32 Detection of Cavities in a Limestone Rock (by 75 mHz and 38 mhz correspondingly), Cavities at 7 m and 18 m Depth

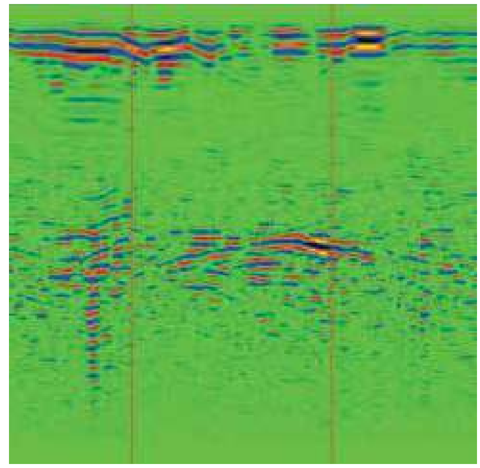


Fig. 33 Detection of a Railroad tunel in a Limestone Rock Covered with 2 m Loam, at 15 m Depth

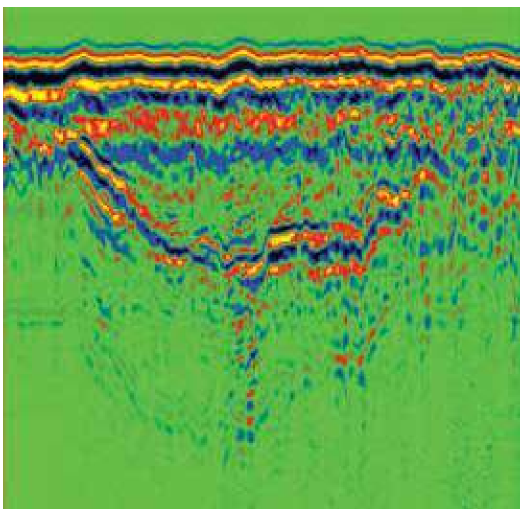


Fig. 34 Profiling of a Sandy hill. 100 MHz surface Coupled Shielded Antenna was used

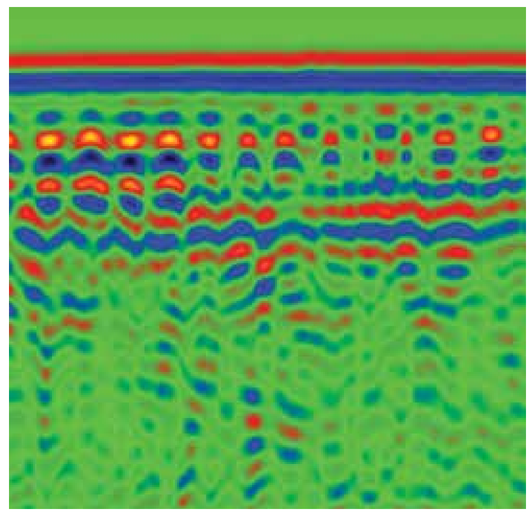


Fig. 35 Detection of Rebars in Concrete Floor. 1500 mHz Shielded Antenna was used

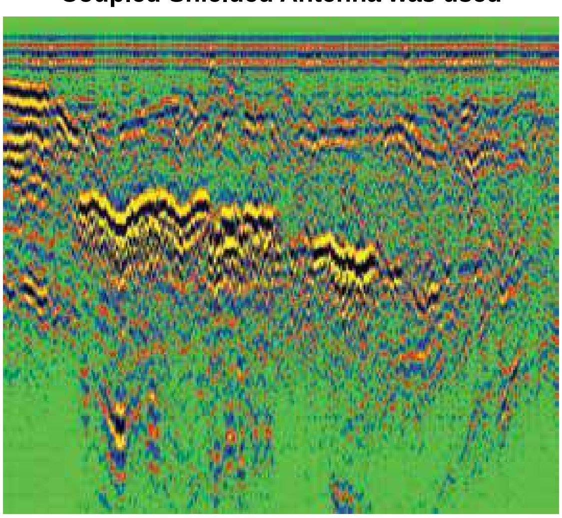


Fig. 36 Sounding of Railways Embankment. 750 mHz Air-coupled Shielded Antenna was used

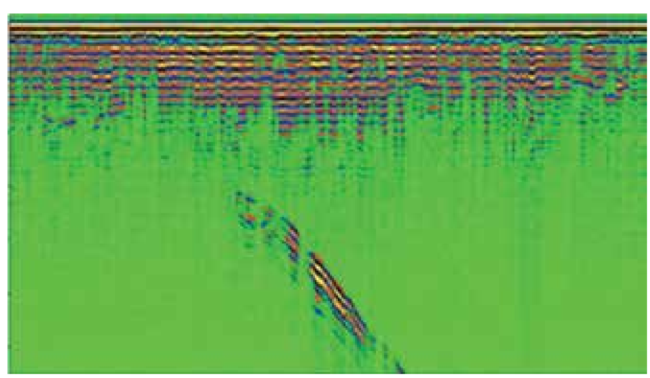


Fig. 37 Detection of Fructure Zone in Permafrost Rock of East Siberia. 150 mHz Dipole Antenna was used

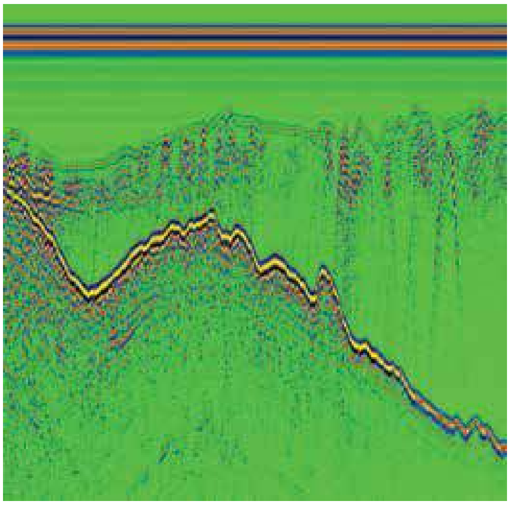


Fig. 38 Profiling of a lake from the bottom of plastic boat. Shilded antenna 500 mHz was used. There are several metalic objects very well visible in silt layer

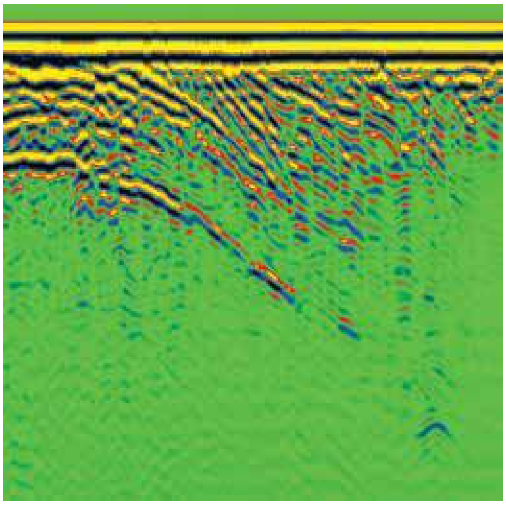


Fig. 39 Profiling of a sandy hill. Movement of a georadar was from the foot of the hill (left) to its top (right). Therefore, signals from the grown water table and various boundaries are drifting down. A major nonuniformity is recorded almost at the top of the hill, at the depth of 35 m. Sounding frequency: 38 mHz

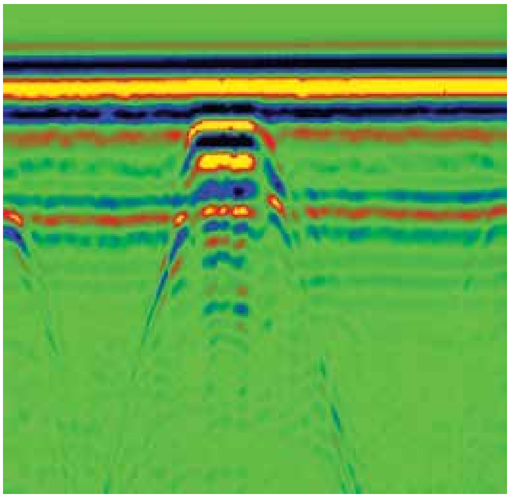


Fig. 40 Sounding of a brick wall. mid-part of the profile clearly shows a signal from an built-in metal cabinet. Sounding frequency: 2 GHz

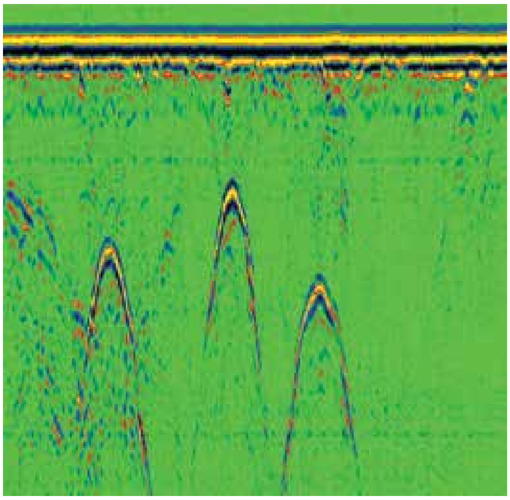


Fig. 41 Detection of three metal pipes buried in soil to the depth of 1.0 to 1.5 m. Each pipe generates a path signal having a hyperbolic shape whose apex corresponds to the pipe location. Sounding frequency: 900 mHz

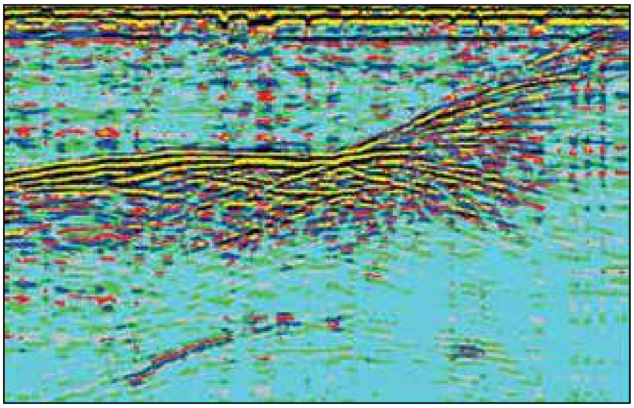


Fig. 42 This profile was obtained by Sounding a Drift Wall in a Salt mine. Well visible signals have a shape of multiple hyperbolas originating from an adjacent drift. Distance between the two drifts is approximately 7.5 m. Sounding frequency: 500 mHz

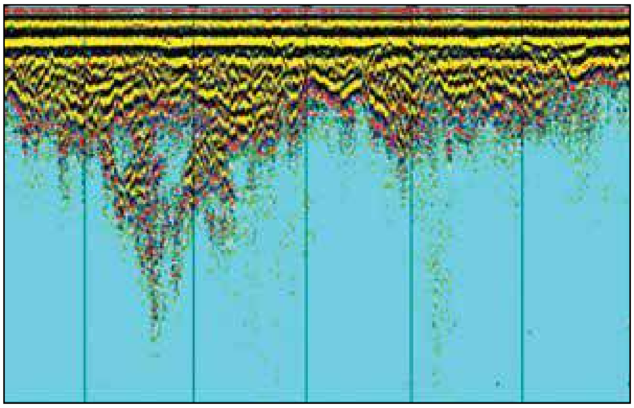


Fig. 43 Profiling of an ancient river bed which is not seen through on the present-day profile. River bed signals are in the left-hand part of the profile. Signals from various lithological boundaries are seen in the upper part of the profile. Sounding frequency: 300 mHz

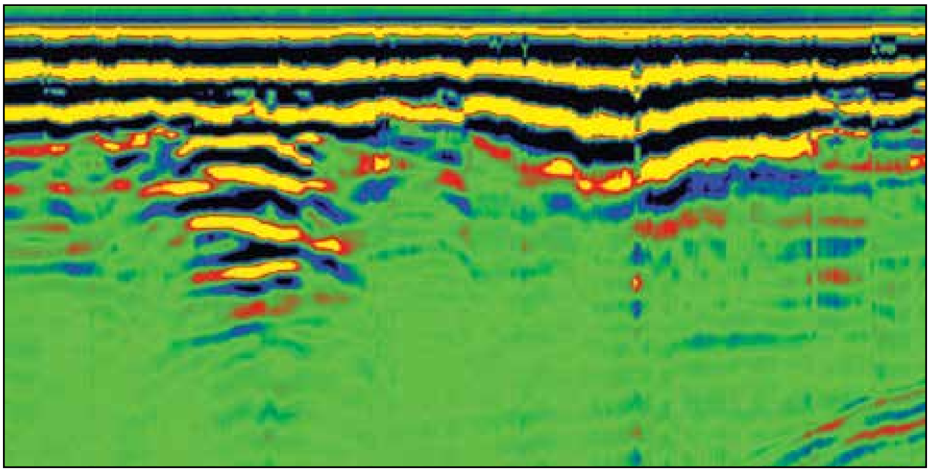


Fig. 44 Detection of a karst cavity in limestone below a loamy layer. The cavity is seen as alternating strips in the left-hand part of the profile. Loam is displayed as a continuous signal in the upper part of the profile. Sounding frequency: 300 MHz.

4.7 Induction Locator method

Radio-detection uses the principles of electromagnetic to detect underground utilities. This principle works on the basis that a current flowing along a conductor creates a magnetic field, which extends around the conductor in concentric circles. A receiver coil can be used to detect the amplitude of this magnetic field. The amplitude varies depending on the position and orientation of the receiver within the field. The amplitude is maximum when the receiver is in line with the field and directly above the conductor. Moving the receiver from side to side it is possible to follow the maximum signal response and, therefore, the line of the buried utility. **Figs. 45, 46** and **47** show instruments, field operation.

Fig. 45 Various Types of Induction Locator Equipments

Both active and passive methods are used to ensure all possible detectable utility services are located properly.

4.7.1 *Active Methods*

An active signal is a signal that has been artificially generated by an external source. Active radio detection methods can allow different services such as BT and electric to be individually identified. Active methods involve the use of a transmitter. The transmitter can either be used for direct connection or for induction. Direct connection involves the application of an active signal to a conductor using a clamp. Induction involves a signal being radiated from the internal antenna of the transmitter, which is induced to any conductors in the vicinity and re-radiated. Generally 8, 33 or 65 KHz frequencies are used. It is often possible to determine the depth of the service in this mode.

4.7.2 *Passive Methods*

A passive signal is a signal that occurs ‘naturally’ on a buried conductor. Passive radio detection methods can provide an indication only that services are present underground. Passive methods use the electro-magnetic fields already present around the underground utility to locate them.

Two modes are generally used:

- Power -detects 50-60 Hz energy present on most buried conductors
- Radio -detects re-radiated radio energy often present on conductors -it is not possible to determine depth in this mode.

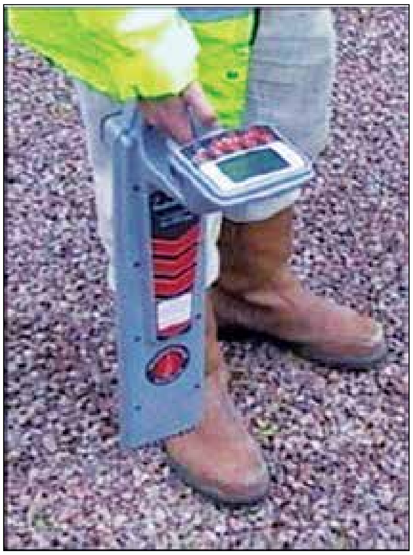


Fig. 46 Induction Locator in Action

Fig. 47 Data Collection in Progress

The radio-detection method, coupled with GPR, provides excellent data on underground utility network.

4.8 Gravity Surveys

Gravimetry is a potential field technique which measures variations in the Earth's gravitational field. These variations are caused by density contrasts in the near surface rock and sediment. Gravimetric surveys are carried out using extremely sensitive instruments capable of measuring tiny variations in the gravitational field. These surveys are always carried out in conjunction with a precise topographic survey, to enable terrain corrections to be carried out. **Figs. 48, 49** and **50** show instruments for gravity surveys and contour maps obtained.

Fig. 48 Gravity Survey Instrument

Fig. 49 Data Collection In Progress

Typical applications are:

i) Regional geological mapping
ii) Oil and gas exploration
iii) Mineral exploration

iv) Sediment thickness studies

v) Archaeological surveys

vi) Void detection

The technique is extensively used for void detection, generally combined with techniques of Ground Penetrating Radar and Electrical Imaging.

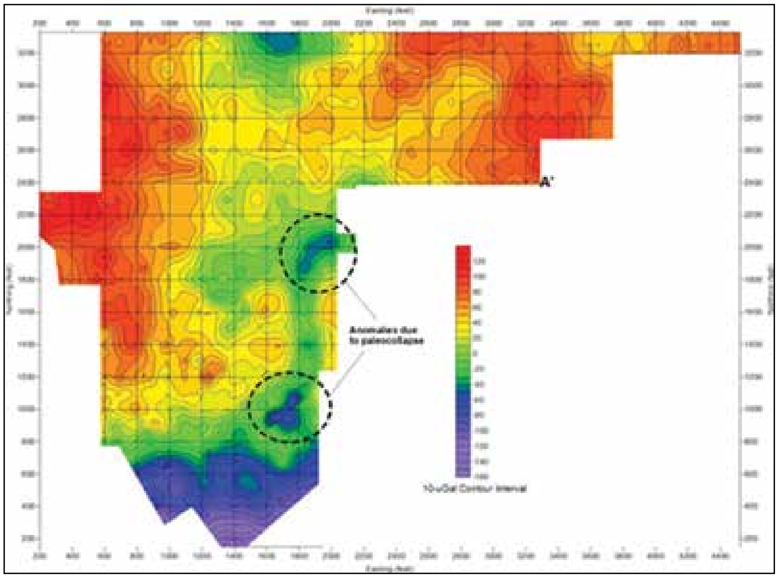


Fig. 50 Typical Gravity Contour map (Courtesy Technos, Inc)

Gravity measurements define anomalous density within the Earth; in most cases, ground-based gravimeters are used to precisely measure variations in the gravity field at different points. Gravity anomalies are computed by subtracting a regional field from the measured field, which result in gravitational anomalies that correlate with source body density variations. Positive gravity anomalies are associated with shallow high density bodies, whereas gravity lows are associated with shallow low density bodies. Thus, voids and cavities are easily detected using micro-gravity method.

4.9 Application of Geophysical Investigation for New Bridges

All major bridge projects where linear water way exceeding 100 m, longer elevated corridors, hilly terrains, flyovers in urban limits and all expected difficult sub soil conditions shall be investigated for geophysical studies prior to geotechnical investigations. The borehole locations for the geotechnical investigations shall be optimised for number of bores and depth of investigation based on geophysical studies already carried out. The geophysical studies can be carried out by a suitable instrument or a combination of many instruments as stated here.

There is no replacement of geotechnical investigation in lieu of geophysical studies. After experiencing the application of geophysical studies in recent times in the country delays in the project execution and cost overruns can be avoided in infrastructure projects.

5 GEOPHYSICAL mETHODS FOR INVESTIGATING THE EXISTING BRIDGE CONDITIONS

The aging and deterioration of bridges mandates increasingly cost-effective strategies for bridge maintenance, rehabilitation, and repair. Use of non-destructive Geophysical methods for evaluating the integrity of structures has grown rapidly over the last decade. Not only do the geophysical methods help to investigate large infrastructures economically to provide comprehensive information about the existing bridge conditions, they help to ensure safety, reduced design uncertainty, mitigate bridge failures and minimize the need for destructive coring/testing.

5.1 Characterizing of Existing Bridge Foundations and Assessing Scour Conditions

Assessing and characterizing geotechnical conditions at existing highway bridges for scour conditions or general foundation adequacy can become complex and costly when difficult access, difficult ground conditions or regulatory constraints limit traditional exploratory methods. Even when traditional methods can be applied, results based on penetration testing and / or recovered samples may be of limited usefulness. When ground surface is available and not completely inundated, surface geophysical methods provide means, for subsurface preliminary or screening characterization under these conditions. Surface geophysics can provide information concerning subsurface geometry and relevant material properties. **Fig. 51** shows typical foundation condition **Fig. 52** shows typical inter-relationship of unknown foundations, characterisation and hydraulic scour.

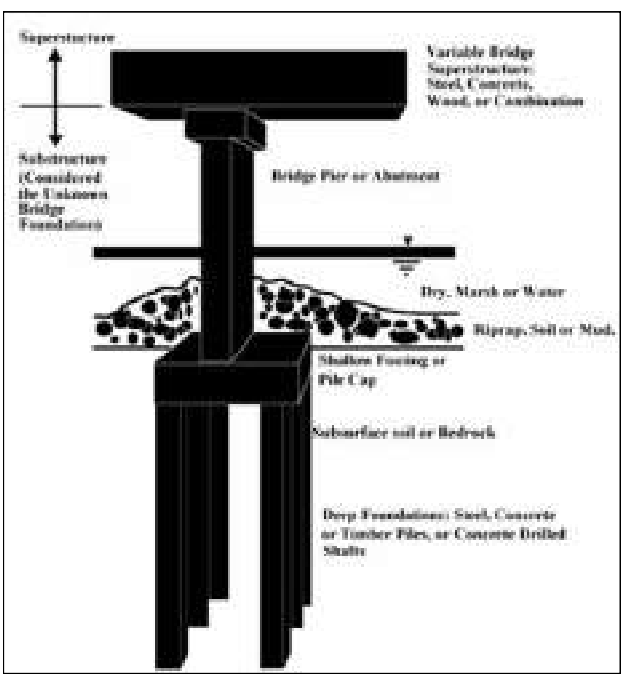


Fig. 51 Typical Foundation Conditions

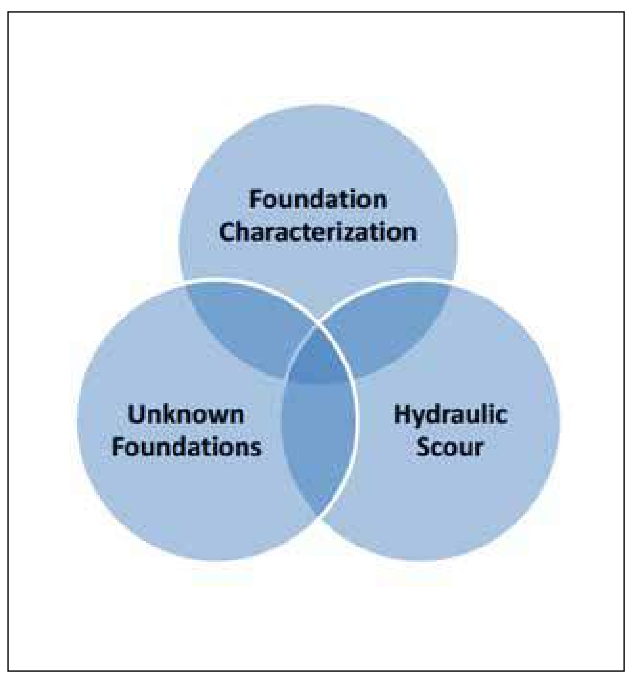


Fig. 52 Typical Inter-Relationship of Unknown Foundations, Characterization and Hydraulic Scour

There are many bridges across the world identified as having unknown foundations. The missing substructure information associated with unknown foundations has made the safety monitoring of these “off-system” bridges very difficult, especially the scour of critical bridges because of the foundation properties like type and dimensions, are essential for determining the bridge vulnerability to scour. Bridge scour is the removal of sediment such as sand and rocks from around bridge abutments or piers. Scour, caused by swiftly moving water, can scoop out scour holes, compromising the integrity of a structure.

While very few studies have used statistical, computational, numerical solutions, soft-computing methods such as Artificial Neural Networks (ANNs) and probabilistic methods such as Bayesian to infer foundation properties, there are a number of studies on applying Non Destructive Testing (NDT) methods to obtain information about unknown bridge foundations, predicting pile depth and reviewing scour depth at bridge piers.

Bridge foundations can be divided into shallow footings or deep foundations. Footings are mostly square or rectangular in shape. They may also be pedestal masonry stone footings or massive cofferdam footings in shape. Piles might be present with or without pile caps and may be battered or vertical. Piles can be made of concrete (round, square, or octagonal), steel (H-piles or round pipe sections), or timber. Deep foundations can be pre-cast concrete piles, or drilled shafts and auger-cast concrete piles. The top of footings or pile caps may be buried underneath riprap, backfill mud and/or channel soils.

Scour of foundations is the number one cause of bridge collapse. Scour occurs in three main forms, namely, general scour, contraction scour and local scour. General scour occurs naturally in river channels and includes the aggradation and degradation of the river bed that may occur as a result of changes in the hydraulic parameters governing the channel form such as changes in the flow rate or changes in the quantity of sediment in the channel. It relates to the evolution of the waterway and is associated with the progression of scour and filling, in the absence of obstacles. Contraction scour occurs as a result of the reduction in the channel’s cross-sectional area that arises due to the construction of structures such as bridge piers and abutments. It manifests itself as an increase in flow velocity and resulting bed shear stresses, caused by a reduction in the channel’s cross-sectional area at the location of a bridge. The increasing shear stresses can overcome the channel bed’s threshold shear stress and mobilize the sediments. Local scour occurs around individual bridge piers and abutments. Downward flow is induced at the upstream end of bridge piers, leading to very localized erosion in the direct vicinity of the structure. **Fig. 53** shows typical schematic of scour process.

Horseshoe vortices develop due to the separation of the flow at the edge of the scour hole upstream of the pier and result in pushing the down-flow inside the scour hole closer to the pier. Furthermore, separation of the flow at the sides of the pier results in wake vortices.

Local scour depends on the balance between streambed erosion and sediment deposition. Clear-water scour is the term given to describe the situation when no sediments are delivered by the river whereas live-bed scour describes the situation where an interaction exists between sediment transport and the scour process. The presence of live-bed conditions leads to smaller ultimate scour depths than in clear-water conditions. The most critical factors contributing to local scour are the velocity and depth of flow, both of which are significantly increased during heavy storms and floods. As the velocity and/or depth increase, the amount of scour increases. Other factors affecting bridge scour include the dimensions and orientation of piers, bed configuration and material size/gradation, and accumulation of ice and debris along the piers.

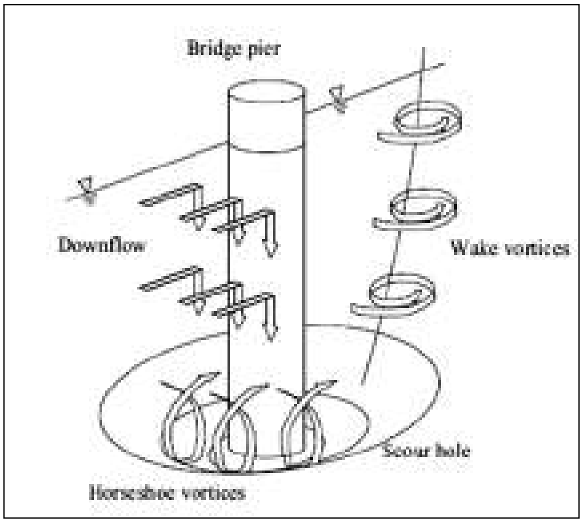


Fig. 53 Typical Schematic of the Scour Process

Scour poses obvious problems to the stability of bridge structures. There are two issues associated with such scour-induced damage to bridge pier footings. The first effect is the loss of foundation material, which exposes the footing and lowers its factor of safety with regard to sliding or lateral deformation. The greatest loss of sediment to scour occurs at high water velocities, such as during floods. Secondly, pier movement may occur because of material loss beside and beneath the base of the footing, which produces undesired stresses in the bridge structure and ultimately results in structural collapse. The scour hole generated has the effect of reducing the stiffness of foundation systems and can cause bridge piers to fail without warning. **Fig. 54** provides for typical foundation with respect to scour.

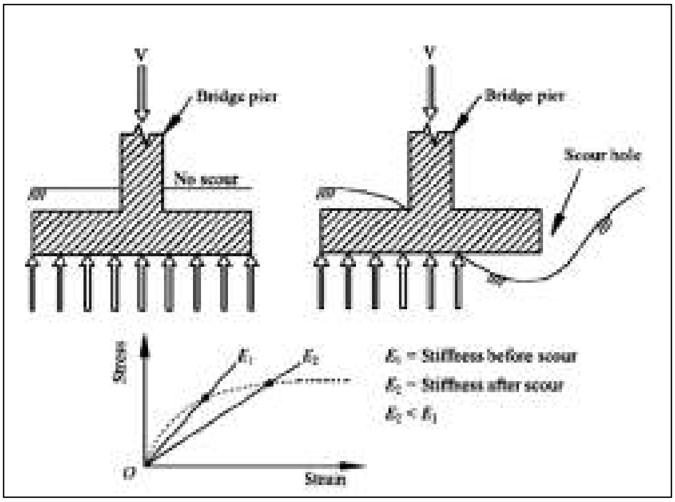


Fig. 54 Typical Reduction in Stiffness Caused by Scour

There are many critical bridges on spread footings or shallow piles. During a flood, scour is generally not visible and during the falling stage of a flood, scour holes generally fill in. Visual monitoring during a flood and inspection after a flood cannot fully determine that a bridge is safe. Instruments to measure or monitor maximum scour would resolve this uncertainty. Geophysical techniques for scour monitoring involve filling-in the vicinity of a bridge pier or footing at scour- critical bridge sites, monitoring of scour elevations and the hydraulic conditions that cause bridge scour, such as water depth, water velocity, bed-material size, channel slope, and channel geometry.

5.1.1 *Time Domain Reflectrometry*

Time Domain Reflectrometry (TDR) uses electromagnetic impulses that travel along a cable and are reflected when they encounter an impedance change. This can occur at the end of the cable or at a break or imperfection. The TDR instrument measures the time that the signal takes to travel along the cable and return to the instrument. Knowing the speed of travel of the wave then allows the travelled distance to be calculated. **Figs. 55** and **56** shows time-domain reflectometry.

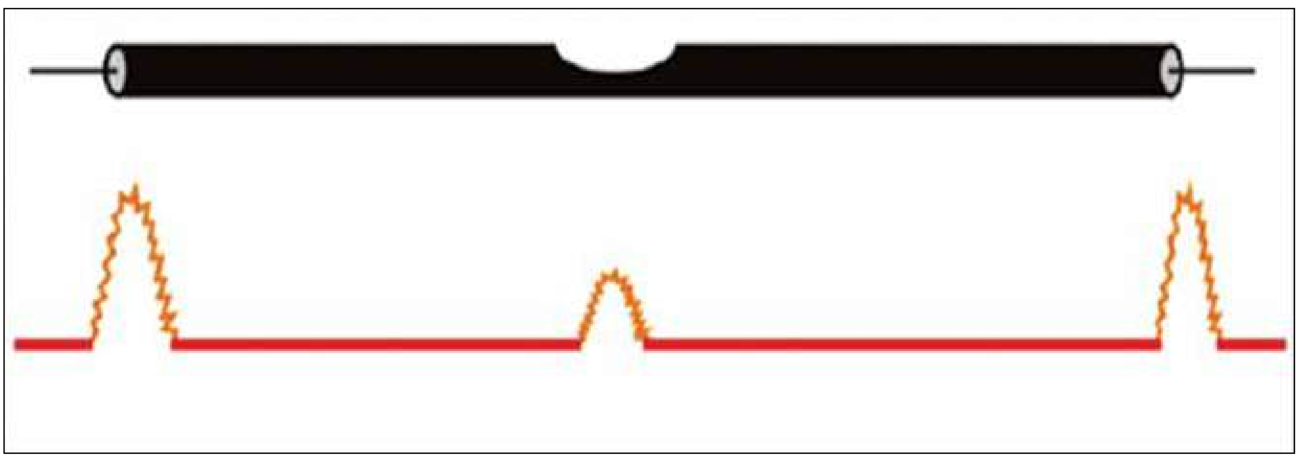


Fig. 55 Typical Time Domain Reflectrometry signals from cable ends and a Thinner Section of the Cable

Measurements of scour at bridges founded on shallow footings indicate maximum scour occurs around the upstream side of footings during floods. As scour progresses and soil deposits are eroded, footings may be exposed and eventually undermined, leading to intolerable pier movement. Optimal placement of TDR cables would, therefore, be through the footing section on the upstream side. Most importantly, the cable monitoring system must operate at high water flows when footing and pier displacement is most likely to occur as a result of scour. Although bridge abutments may be less affected by scour, under certain circumstances they may need to be monitored for detrimental movements.

Pier footing movements can be detected from voltage reflections generated by local cable deformation. A minimum cable deformation of 2 mm produces a distinguishable voltage reflection in the TDR signal. Further footing displacement progressively shears the cable and produces increasingly larger voltage reflections at that point along the cable.

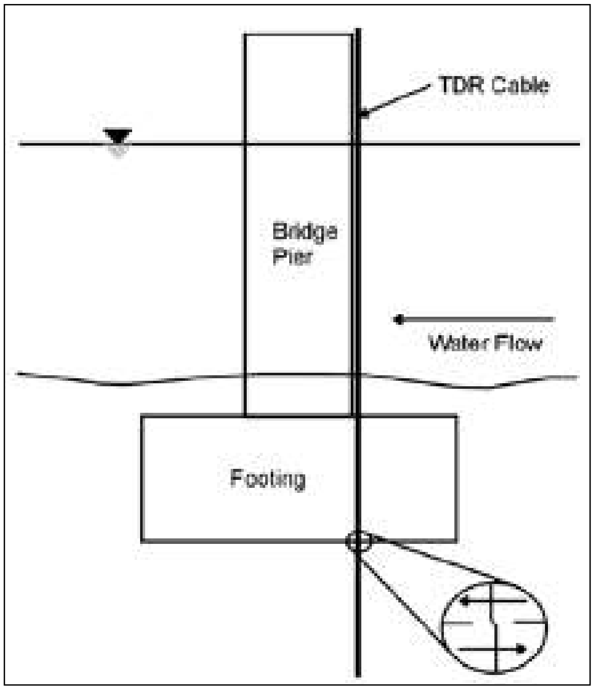


Fig. 56 Typical Cable installation for Time Domain Reflectrometry Measurements at a Pier

5.1.2 *Ground Penetrating Radar*

In bridge scour evaluations, the Ground Penetrating Radar (GPR) method can provide an essentially continuous image of the stream channel and the sub-bottom sediment, including the in-filled scour features. Estimated Electromagnetic velocities can be used to transform the time-depth profile into a depth profile since velocities are a function of suspended sediment load. This method uses radar pulses to determine the water sediment interface and hence the depth of scour. A floating GPR transmitter is pulled along the water surface thus obtaining a geophysical profile of the riverbed as it passes. It operates by sending out high frequency electromagnetic waves which are partially reflected as they pass through different media, thus building up a geophysical map of the subterranean lithology. **Figs. 57** and **58** shows typical data collected at a bridge location.

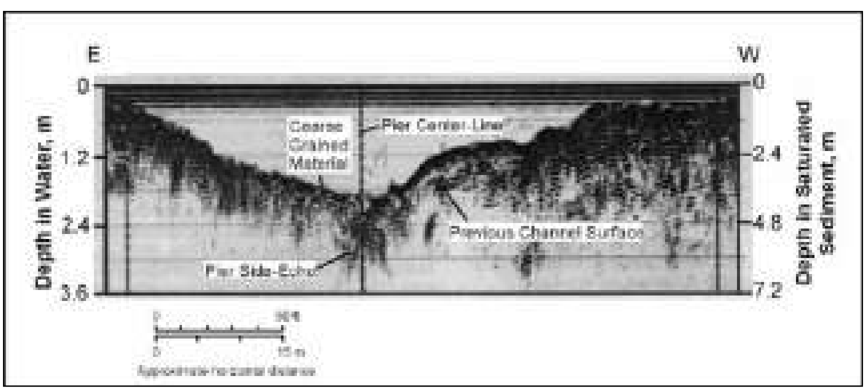


Fig. 57 Typical Unprocessed 300 mHz Ground Penetrating Radar data collected 2 feet upstream from a pier. (Placzek, et al. 1995, USGS Report 95-4009)

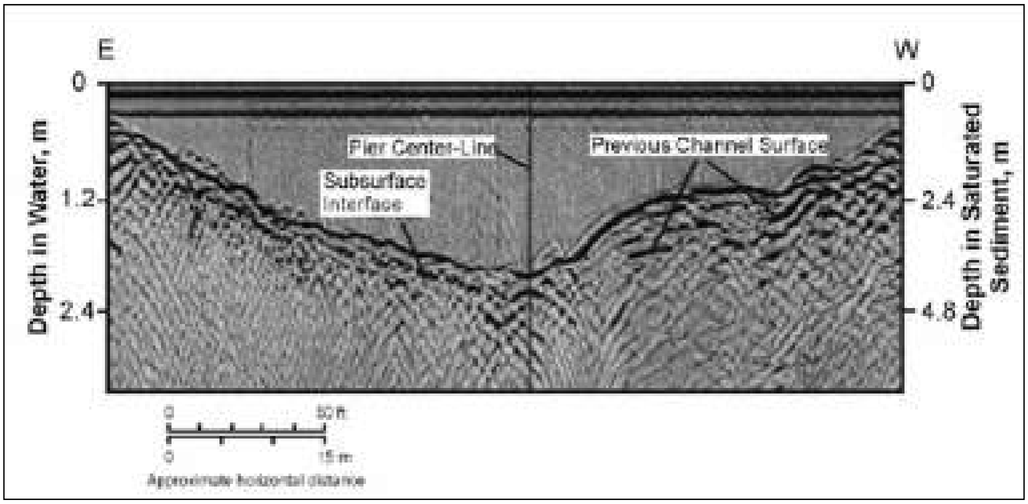


Fig. 58 Typical Digitally Filtered and migrated 300 mHz Ground Penetrating Radar data. (Placzek, et al. 1995, USGS Report 95-4009)

The main advantages of the GPR profiling tool are as follows:

i) The GPR antennae are non-invasive and can be moved rapidly across (or above) the surface of a stream at the discretion of the operator. The GPR tool does not need to be physically coupled to the water surface and can be operated remotely, ensuring that neither the operator nor equipment need be endangered by floodwaters. Profiles can be extended across emerged sand bars or onto the shore.

ii) The tool can provide an accurate depth-structure model of the water bottom and sub-bottom sediments (to depths on the order of 9 m). Post acquisition processing (migration) can be applied.

iii) Lithologic/facies units with thickness on the order of 0.1 m can be imaged with intermediate-frequency units (200 MHz).

The main limitations of the GPR profiling tool are as follows:

i) The equipment is relatively expensive (hardware and software).

ii) Data may be contaminated by noise (multiple reflections and echoes from pier footings).

iii) Post-acquisition processing (migration) may be required in areas where significant structural relief is present.

iv) GPR is not normally effective when water depths exceed 9 m.

v) GPR cannot be used in saline waters.

5.1.3 *Sonic Fathometers*

A number of devices have been developed that use sound waves to monitor the progression of scour holes. They work on the same principle as devices that use electromagnetic waves, in that waves are reflected from materials of different densities thus establishing the location of the water sediment interface.

Sonic fathometers can be mounted on bridge piers just below the level of the water stage. They build up continuous profiles of the streambed by emitting sonic pulses from a pulse generator, which travel through the medium to the water sediment interface. In doing so, the device can detect and monitor the depth of scour over time. The device can, however, only be operated within certain depth tolerances and is susceptible to interference from entrained air present in highly turbulent flow. In addition, at the place where the bed topography is variable, this type of sensor only measures the shallowest depth. Therefore, the beam width at the bed with respect to the scour hole may significantly affect the accuracy of the scour depth measurements. **Fig. 59** shows typical data from fathometers.

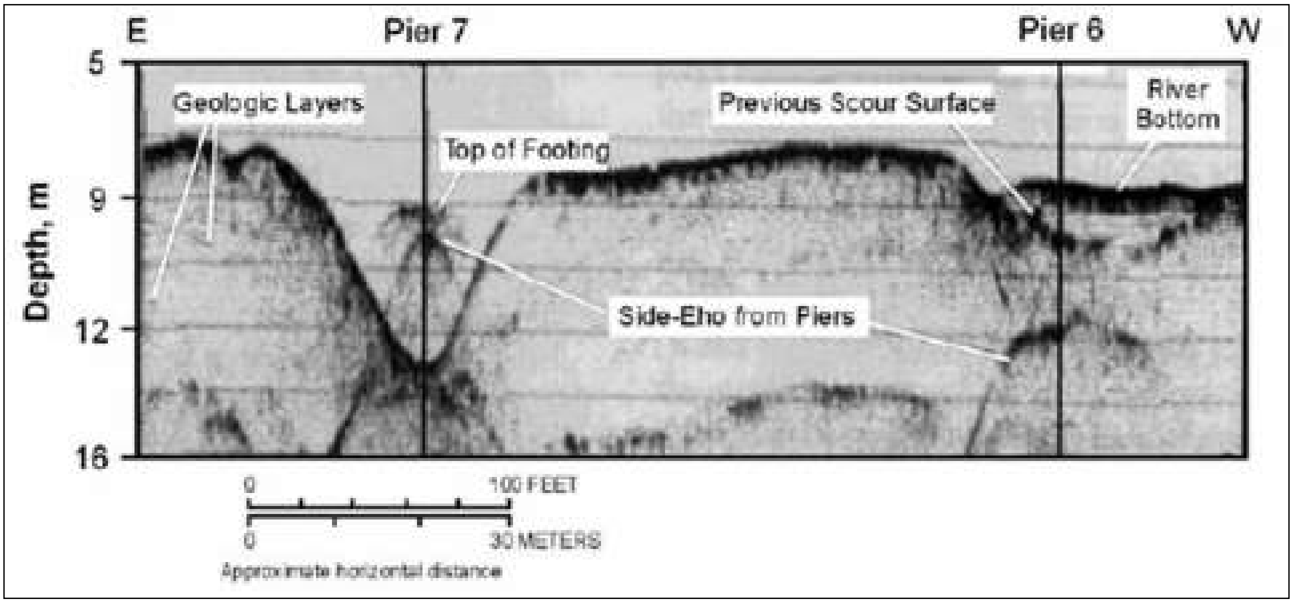


Fig. 59 Typical Fathometer Data Recorded using a 3.5 kHz Transducer

5.1.4 *Reflection Seismic Profilers*

Reflection seismic profilers also utilize sound waves to monitor and detect scour. This device typically employs a coupled acoustic source transducer and receiver transducer that are placed immediately below the water surface. As the system is towed manually across the water surface, the source transducer produces short period pulsed acoustic signals at regular time or distance intervals. The high frequency seismic pulse propagates through the water column and into the subterranean sediments below. This device can build up profiles of the streambed as some of the acoustic energy is reflected back to the receiver when the water sediment interface is encountered. By combining the signals from multiple locations and using estimated seismic interval velocities, the time depth profile can be converted into a depth profile.

The frequency of the seismic signal used by the Continuous seismic profiling technique determines the maximum penetration depth and resolution. A high-frequency signal has a short wavelength and is attenuated by sub bottom materials but provides high resolution of sub bottom interfaces. A low-frequency signal has a longer wavelength and is attenuated less by sub bottom materials but provides lower resolution. The fixed-frequency CSP technique uses a narrow bandwidth fixed-frequency signal usually centered at 3.5, 7.0, or 14 kHz. The CSP technique using a 14 kHz signal can be used in water as shallow as 1.2 m, can penetrate up to 6 m into the sub bottom in certain materials, and can detect fill material as thin as 30 cm in a scour hole. The CSP technique using a 3.5 kHz signal can be used in water as shallow as 2 m, can penetrate up to 30 m into the sub bottom in certain materials, and can detect fill material as thin as 75 cm in a scour hole. Swept-frequency (chirp) CSP techniques that sweep from 2 to 16 kHz can be used in water as shallow as 30 cm, and can penetrate 60 m into the sub bottom in silts and clays. Such signals can sometimes detect fill material as thin as 8 cm in a scour hole. **Figs. 60** and **61** shows typical data obtained.

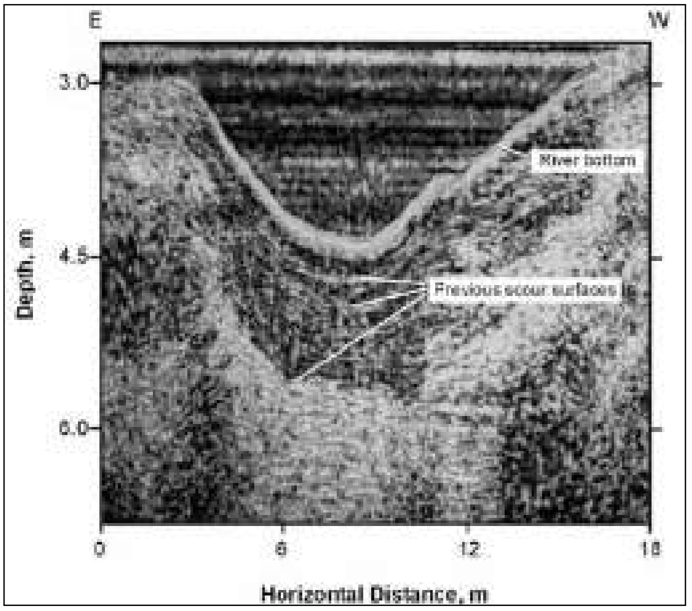


Fig. 60 Typical Continuous Seismic Profiling Data Recorded with a 14.4- kHz Transducer of a Single Frequency System

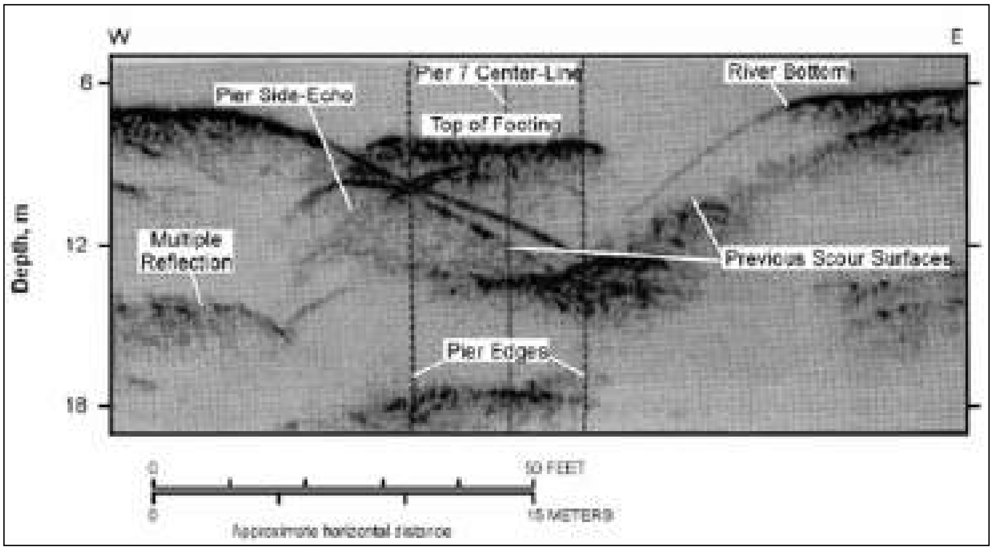


Fig. 61 Typical Continuous Seismic Profiling swept frequency data using 2-16 kHz transducer of a swept frequency system.

5.1.5. *Echo Sounders*

Echo sounders work in a very similar manner to reflection seismic profilers and can be used to determine scour hole depths. The only major difference is that they emit higher frequency acoustic source pulses and due to the rapid attenuation of the high frequency pulsed acoustic energy, relatively little signal is transmitted or reflected within the sub-bottom sediment. A time-depth profile is generated by plotting traces from adjacent source and receiver locations. Using estimated seismic interval velocities, these plots may be converted to depth plots. The only disadvantage of this system over reflection seismic profilers is that no information about previously filled-in scour holes can be obtained since the high frequency waves cannot penetrate into the sub-bottom strata.

Devices of this type use the differences in the electrical conductivity of various media to determine the location of the water sediment interface. They work on the principle of measuring an electrical current between two probes. If the material between the probes changes, the ability for a current to be drawn will also change. This phenomenon can be used to indicate the presence and depth of scour. An example of a device that uses this technology is electrical conductivity probe. **Fig. 62** shows typical scour monitory instrumentation.

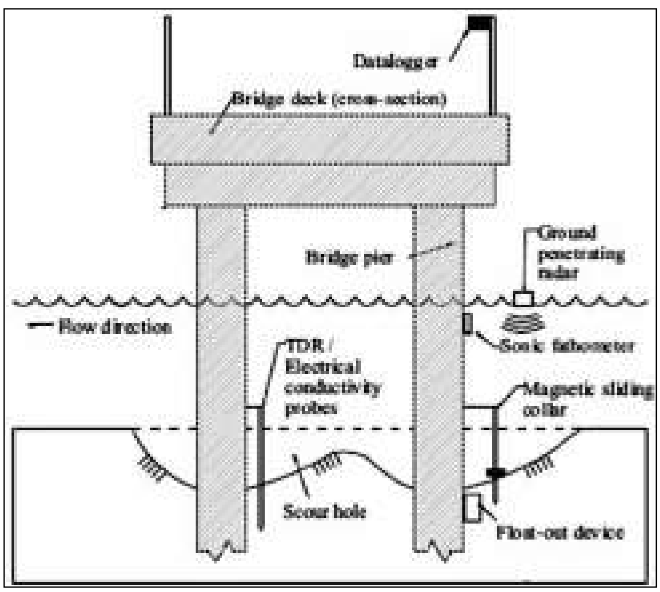


Fig. 62 Typical Scour monitoring Instrumentation

5.2 Depth and Integrity Investigations of Existing Bridge Foundations

5.2.1 *Sonic Echo/Impulse Response Test*

The sonic echo/impulse response test can be used to evaluate the integrity and length of newly constructed piles. It can be used to detect defects, soil inclusions and pile necking, diameter increases (bulging) as well as approximate pile lengths. The Sonic Echo method requires a measurement of the travel time of seismic waves (time domain), and the Impulse Response method uses spectral analysis (frequency domain) for interpretation. These two methods are sometimes called Pile Integrity Testing methods (PIT).

In both (SE/IR) tests, the reflection of compressional waves, also called P waves by geophysicists, from the bottom of the tested structural element or from a discontinuity such as a crack or a soil intrusion is measured. The generated wave from an impulse hammer travels down a shaft or a pile until a change in acoustic impedance which depends on velocity, density, and changes in diameter is encountered, where the wave reflects back and is recorded by a receiver placed next to the impact point.

In an SE/IR test, a hammer strikes the foundation top, and a receiver monitors the response of the foundation. A digital signal analyzer records the hammer input and the receiver output. Sonic Echo (SE) tests are typically performed with different frequency filtering to optimize reflections coming from the bottom of the foundation and to reduce the effect of surface waves or reflections from a discontinuity at a shallow depth where the frequencies associated with these two conditions are high. In an Impulse Response (IR) test, a digital analyzer automatically calculates the transfer and coherence functions after transforming the time records of the hammer and the receiver to the frequency domain. **Fig. 63** shows typical sonic echo test details.

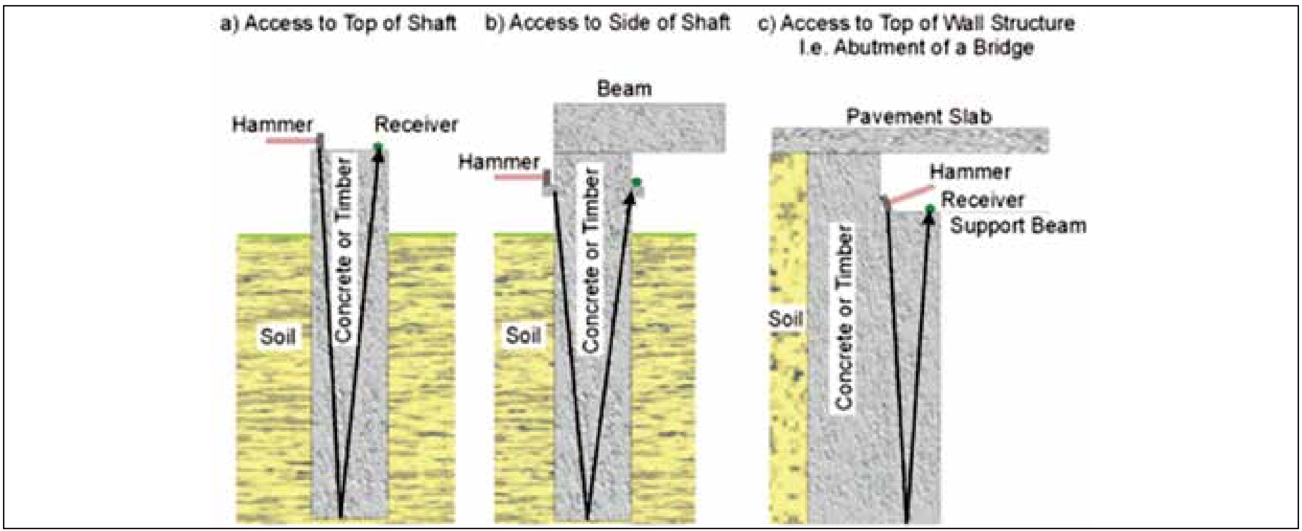


Fig. 63 Typical Configurations Source and Receiver Locations for a Sonic Echo/Impulse Response Test for Three Shaft Geometric Configurations

Sonic Echo data are used to determine the depth of the foundation based on the time separation between the first arrival and the first reflection events or between any two consecutive reflection events (Δt) according to the following equation:

$$D = V \times \frac{\Delta t}{2},$$

where D is the reflector depth, and V is the velocity of compressional waves.

A reflector can be the bottom of the foundation or any discontinuity along the embedded part of the foundation. The Sonic Echo data can also be used to determine the existence of a bulfing or a necking in a shaft or the end conditions of the shaft based on the polarity of the reflection events.

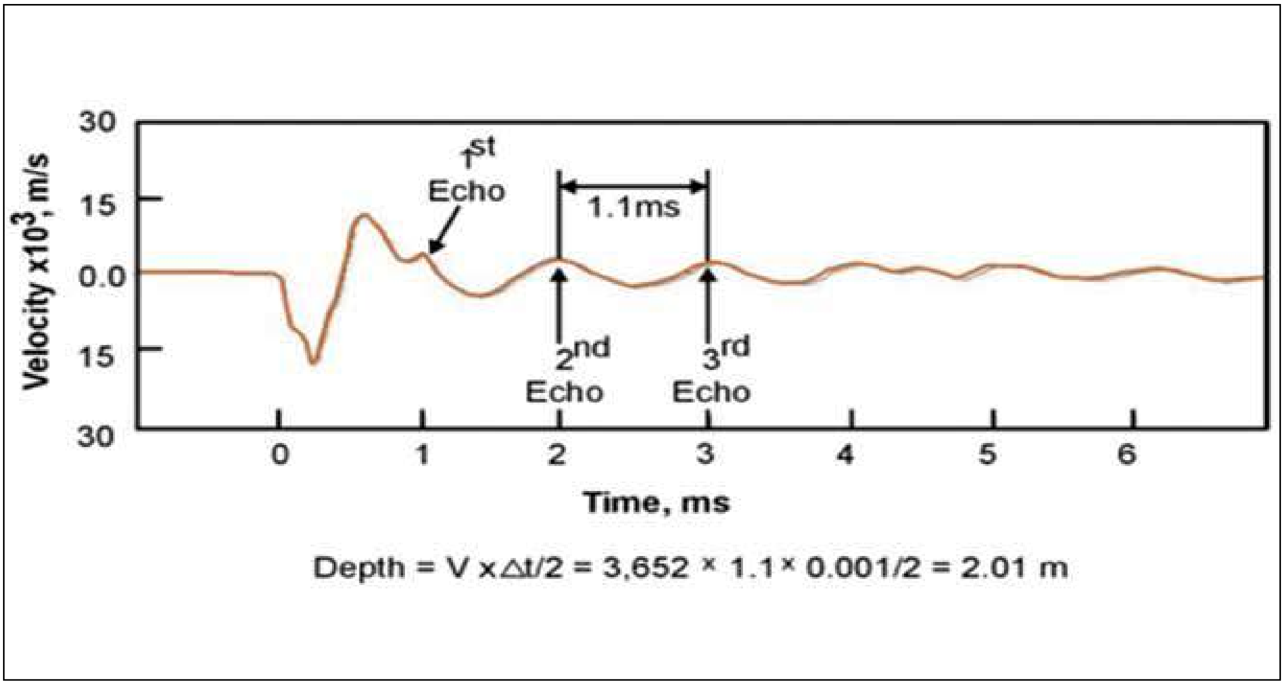


Fig. 64 Typical Data from the Sonic Echo method and Depth Calculations

Fig. 64 illustrates the data from a Sonic Echo survey along with the depth calculation computed between the second and third echoes. The multiple echoes are all interpreted as coming from the same reflector since the time separations of the echoes are all equal. Any pair can be used to calculate the two-way travel time between the source and the reflector. In this case the clearest pair of echoes were the second and third, which were used to calculate the depth using the formula above, giving a depth of 2.01 m.

The Impulse Response data are also used to determine the depth of reflectors according to the following equation:

$$D = \frac{V}{(2 \times \Delta f)},$$

Where, Δf = distance between two peaks in the transfer function plot or between zero frequency and the first peak for soft bottom conditions.

The multiple echoes from a discontinuity or bottom, as seen in the Sonic Echo method, result in increased energy at the frequency of the echo. This causes a peak in the frequency spectrum. Under conditions where there is a hard material beneath the structure, the second harmonic of the echo is also evident. Using the frequency difference between zero and the main echo 10 frequency or between the first and second harmonic frequencies in the formula above gives the depth of the structure. In addition, the Impulse Response data provides information about the dynamic stiffness of the foundation. This value can be used to predict foundation behaviour under working loads or correlated with the results of load tests to more accurately predict foundation settlement. **Fig. 65** illustrates about impulse response method.

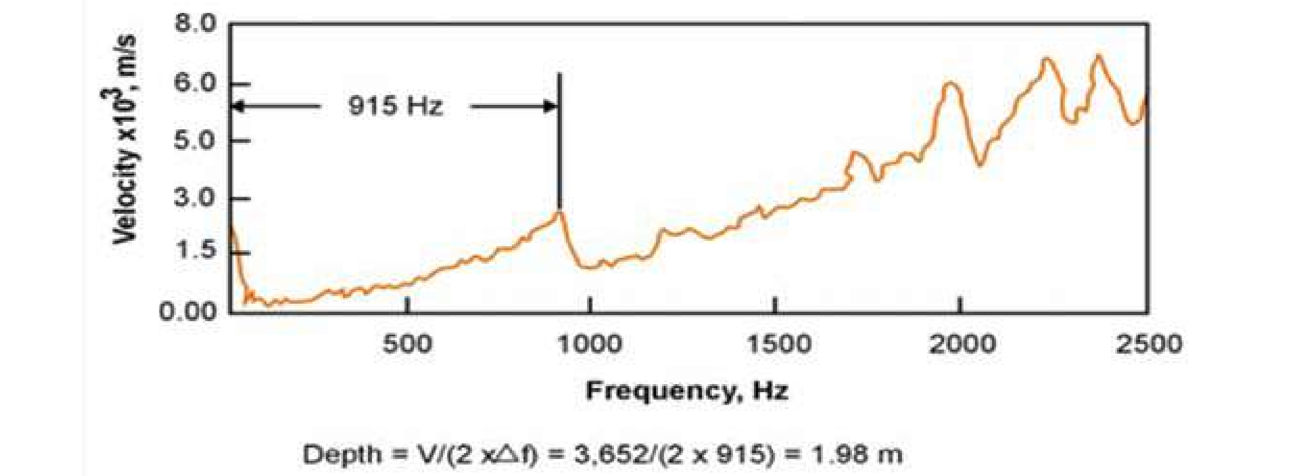


Fig. 65 Typical Depth calculations using Frequency Domain Data for the Impulse Response method

The Bending Waves method uses flexural or bending waves, rather than the compressional waves used in the Sonic Echo/Impulse Response method to determine integrity and unknown depth of deep foundations. It is limited to applications on rod-like deep foundations such as timber piles, concrete piles, and drilled shafts that extend above the ground or water surface. This method uses the propagation of flexural or bending waves in piles that are highly dispersive in nature. The bending wave velocity decreases with increasing wavelength, with most of the velocity decrease occurring at wavelengths that are longer than the pile diameter. These longer waves propagate as flexural or bending wave energy.

The Ultraseismic (US) method is also performed to evaluate the integrity and determine the length of shallow and deep foundations. This method is particularly useful in testing abutments and wall piers of bridges because of the relatively large exposed areas available for testing.

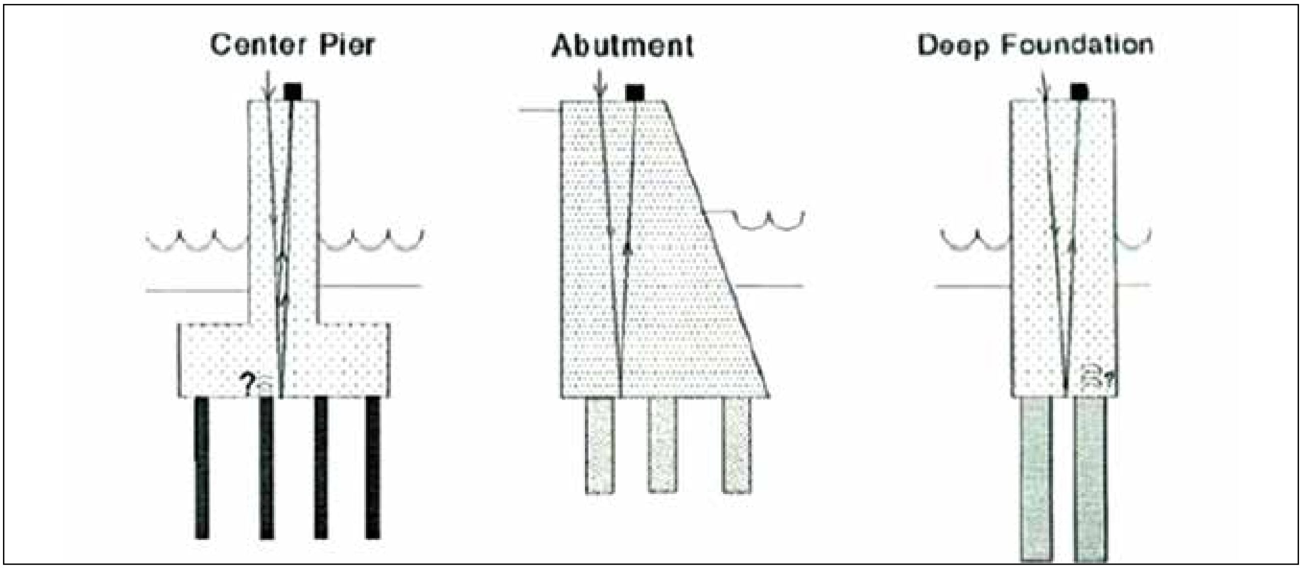


Fig. 66 Typical Impedance of Wave Propagation by Complex Foundations

It uses multi-channel, three-component (vertical and two perpendicular horizontal receivers, i.e., triaxial receiver) recording acoustic data followed by computer processing techniques adapted from seismic exploration methods. Seismograph records are typically collected by using impulse hammers as the source, and accelerometers as receivers that are mounted on the surface or side of the accessible bridge substructure at intervals of 30 cm or less. The bridge substructure element is used as the medium for transmission of the seismic energy. Four wave modes of longitudinal (compressional) and torsional (shear) body waves as well as flexural (bending) and Rayleigh surface waves can be recorded by this method. Seismic processing can greatly enhance data quality by identifying and clarifying reflection events that are from the foundation bottom and minimizing the effects of undesired wave reflections from the foundation top and attached beams. For concrete bridge elements, useful wave frequencies up to 4 to 5 kHz are commonly recorded. **Figs. 66, 67** and **68** shows about typical impedance of wave propagation.

This method can be used in two modes: Ultraseismic Vertical Profiling (VP) and Horizontal Profiling (HP).

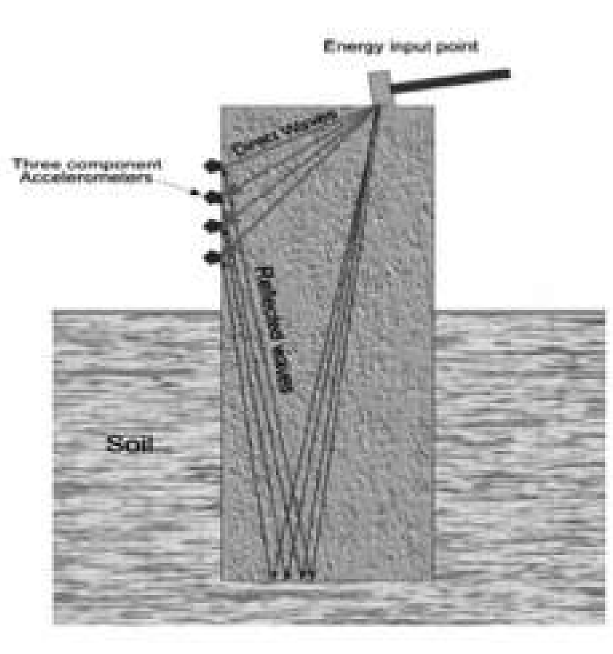


Fig. 67 Typical Ultraseismic Test method and Vertical Profiling Test Geometry

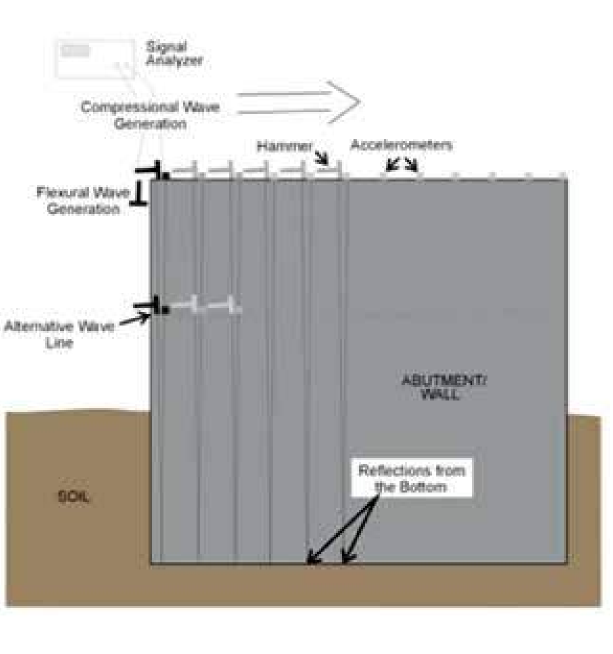


Fig. 68 Typical Ultraseismic Test method and Horizontal Profiling Test Geometry

5.2.2 *Seismic Wave Reflection Survey*

In the Seismic Wave Reflection Survey Method, it involves setting up shot points on one side of the pier and two horizontal component geophones on the other side of the pier. The toe of the pier will diffract seismic waves passing under it. The depth of the pier can be found from the position of the diffractions on the seismic records. **Figs. 69, 70, 71, 72** and **73** shows seismic reflector survey.

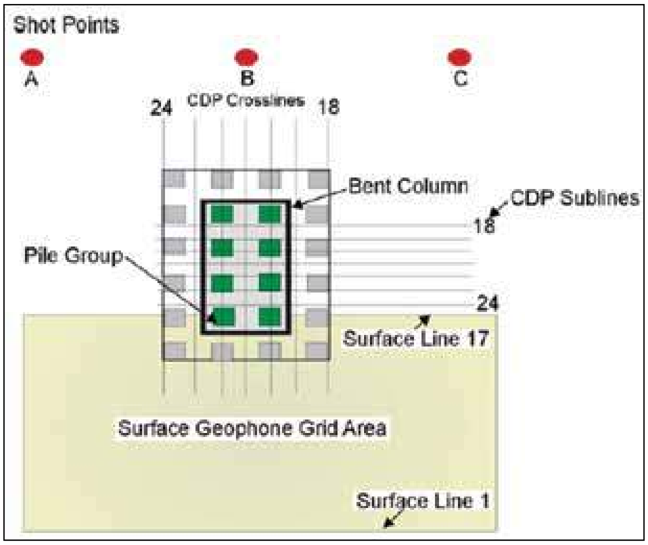


Fig. 69 Typical Shot and Receiver Layout for Seismic Reflection Survey (Plan View)

5.2.3 *Parallel Seismic Method*

The Parallel Seismic (PS) method is a borehole test method for determining depths of foundations. It can also be used to measure the thickness of the scour zone when it has been filled with mud or soft sand after the flood surge has passed. The method can also detect major anomalies within a foundation as well as provide the surrounding soil velocity profile. The method requires the installation of cased borehole close to the foundation being tested. The method can be used when the foundation tops are not accessible or when the piles are too long and slender (such as H piles or driven piles) to be testable by sonic echo techniques.

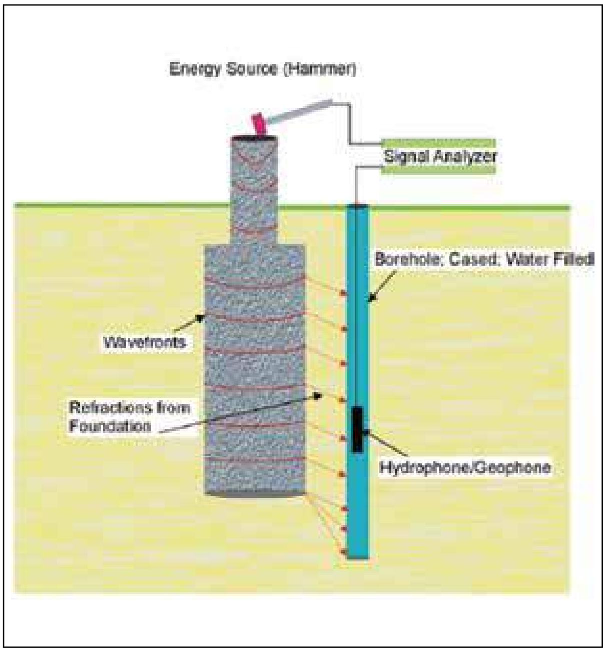


Fig. 70 Typical Parallel Seismic Survey Setup

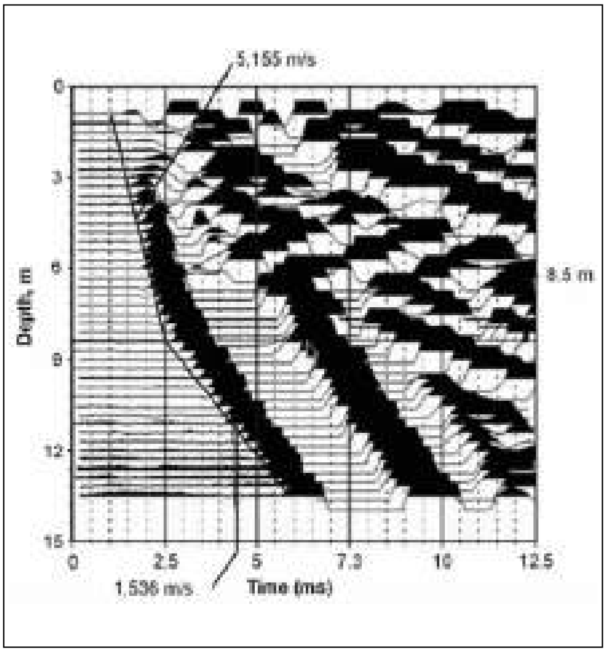


Fig. 71 Typical Parallel Seismic Data and Velocity Lines

Plotting the first arrival times as a function of depth and observing the depth where a change of slope occurs shows the depth to the bottom of the shaft and the scour depth. In addition, the foundation depth can be obtained by observing the depth where the signal amplitude of the first arrival energy is significantly reduced.

For hydrophone data, the time arrival of compressional waves is picked from the data for all receiver locations. A plot of the time arrival-versus-depth is prepared. In **Fig. 71**, the velocity of the concrete in the shaft is 5,155 m/s. A break in the graph occurs at a depth of 8.5 m indicating the depth of the shaft.

For uniform soil conditions, two lines are identified in the plot as shown in **Fig. 72**. The slope of the upper line is indicative of the velocity of the tested foundation, and the second line is indicative of the velocity of the soil below the bottom of the foundation. The intersection of the two lines gives the depth of the foundation. For nonuniform soil conditions, the interpretation of data from hydrophone use can be difficult due to the nonlinearity of the first time arrival. For geophone data in uniform soil conditions, the data can be interpreted in a way similar to the hydrophone data. When variable soil velocity conditions exist, an alternative to the first arrival time in data interpretation is used. All the traces are stacked, and a V-shape is searched for in the data because the bottom of the foundation acts as a strong source of energy (a point diffractor and a reflector), which produces upward and downward traveling waves. When a geophone is used, the borehole is generally not filled with water. As a result, tube waves are minimized so that later arrival of reflected and diffracted shear and compressional waves can be identified.

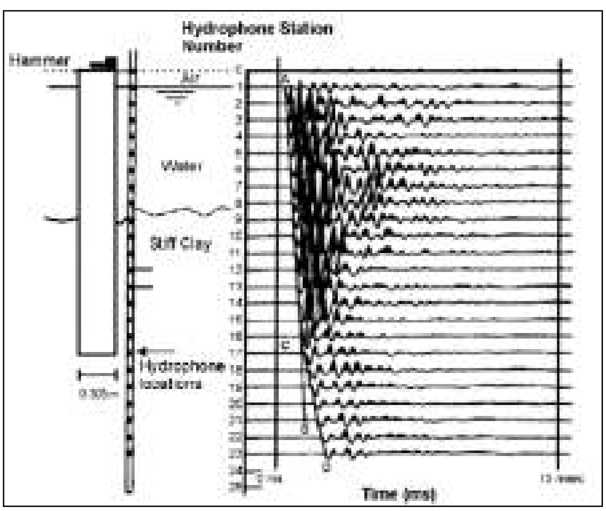


Fig. 72 Typical No scour case. Data not filtered. Note the uniform data amplitudes across the water-sediment interface. The linear refraction first-arrival pattern A-B changes to the hyperbolic first-break pattern C-D at C, which occurs at the base of the pier.

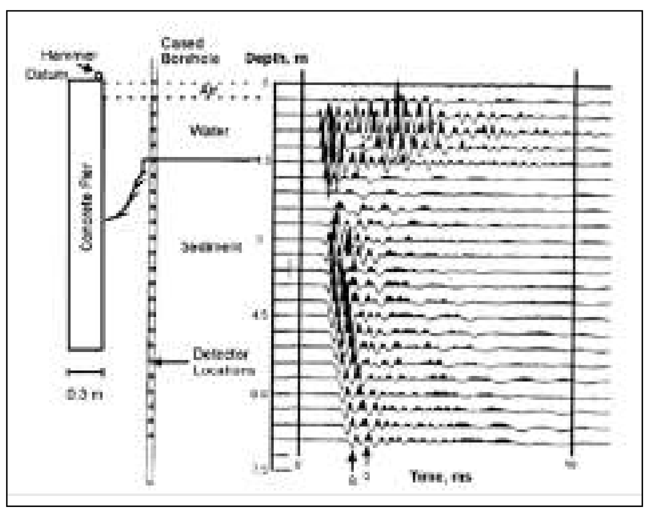


Fig. 73 Typical Scour case. Data not filtered. Note strong attenuation of data amplitudes where energy traverses the mud-filled scour zone.

5.2.4 *Induction Field Method*

Induction Field (IF) method is used for the determination of the unknown depth of steel or continuously reinforced concrete piles. This is an electrical method that relies on detecting the magnetic field in in response to an oscillating current impressed into a steel pile. In order for this method to work, the pile must, therefore, contain electrically conductive materials. For reinforced concrete piles, this usually implies that reinforcing rebar extends along its full length.

A sensor is placed down a drill hole located close to the pile and detects the changing magnetic field strength. This sensor could be a magnetic field sensor or a coil. Along the length of the pile, the magnetic field strength will be relatively strong. However, the magnetic field strength will be significantly diminished at levels in the drill hole beneath the bottom of the pile to a residual conductivity value of the soil or bedrock. This change in the magnetic field strength is used to determine the depth of the pile. **Fig. 74** shows typical induction field method setup.

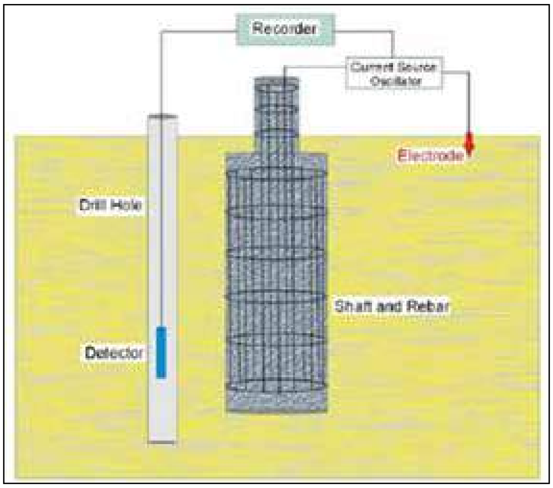


Fig. 74 Typical Induction Field method setup

5.2.5 *Dynamic Foundation Response Method*

The Dynamic Foundation Response uses the resonant frequencies of structures to differentiate foundation types. The vibration response of a bridge substructure will exhibit lower resonant frequency responses when excited for a shallow foundation versus the comparatively higher resonant frequency response of a deep foundation system. The method is unproven for this use in bridges, but is based on the dynamic analysis theory for vibration design of foundations (soil dynamics) and geotechnical analyses of foundations subjected to earthquake loading.

A hammer with a built-in dynamic force transducer is used as the vibration source. A triaxial block of seismic accelerometers records the resulting signals. Typically, a bridge is excited at five to six locations, and the triaxial response is measured at five to six locations giving rise to 25 to 36 source-receiver combinations. The bridges are impacted in the vertical and horizontal directions to excite these modes as well as rocking modes along the frame of the substructures. Once the impulse force and the resultant vibration response are measured, the transfer function can be calculated.

5.2.6 *Vibroseis Trucks Method*

Use of **vibroseis trucks** for inducing vibrations to excite a bridge is also a widely used practice for unknown foundation depth testing. The Piezoelectric Charge Accelerometers are attached to a bridge pier nondestructively. These sensors measure acceleration in three directions and send it directly to a data logger. By impacting the pier with a hammer, readings from the sensors are used to calculate the natural frequency of the pier from which the depth of the foundation can be inferred. A numerical simulation employing the finite element method is also created. In this model, shallow foundations are compared to deep foundations, each with different embedment depths. An eigenvalue analysis with frequencies and mode shapes for each system is created to compare the different responses of frequency relative to the foundation depth and type.

5.2.7 *Crosshole Seismic Tomography*

Two- and three-dimensional tomography is used for the high resolution imaging of the subsurface between boreholes.

Basic Concept: Tomography is an inversion procedure that provides for two- or three-dimensional (2-D and 3-D) velocity (and/or attenuation) images between boreholes from the observation of transmitted first arrival energy.

Data Acquisition: Tomography data collection involves scanning the region of interest with many combinations of source and receiver depth locations, similar to medical CAT-SCAN (fig. below). Typical field operation consists of holding a string of receivers (geophones or hydrophones) at the bottom of one borehole and moving the source systematically in the opposite borehole from bottom to top. The receiver string is then moved to the next depth location and the test procedure is repeated until all possible source-receiver combinations are incorporated. **Fig. 75** illustrates Tomographic survey design.

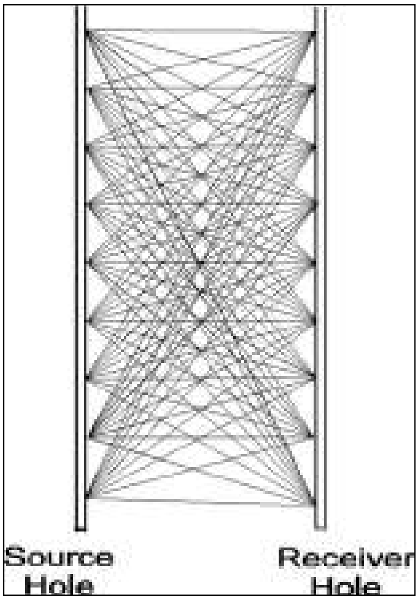


Fig. 75 Tomographic Survey Design

Data Processing: In the tomographic inversion technique, the acoustic wavefield is initially propagated through a presumed theoretical model and a set of travel times are obtained by ray-tracing (forward modeling). The travel time equations are then inverted iteratively in order to reduce the Root Mean Square (RMS) error between the observed and computed travel times. The inversion results can be used for imaging the velocity (travel time tomography) and attenuation (amplitude tomography) distribution between boreholes.

Data Interpretation: Described below in figure is a tomographic survey designed to investigate the foundation of an existing bridge. In this example, cross- hole velocity tomography surveys were conducted by pairing a seismic source in one borehole and a string of receivers in an adjacent borehole to propagate and capture seismic signals transmitted between source and receiver boreholes. Steel or concrete piles that existed within the surveyed area were indicated in the tomograms as relatively higher seismic velocity zones than the surrounding ground. The pile group, as depicted in Figure, appeared as relatively higher seismic velocity anomalies within the fill and soil material above the bedrock. There was also a clear indication of low-velocity anomaly pockets in the top of the bedrock where the piles were driven into the bedrock. The seismic tomography survey indicated that the piles were point-bearing on rock, and, in fact, the piles were driven into the bedrock surface when installed.

The example shown in **Fig. 76** is a tomographic survey designed to investigate the depth of four drilled shafts supported by a pile cap under a bridge column. The shafts were originally thought to be 2 m socketed in the bedrock. The tomogram sections, however, show that the shafts rested on top of bedrock. The results were also confirmed using the parallel seismic method. In figure, the top of bedrock was well defined with no low-velocity anomalies apparent. In this **Fig. 76**, the water-saturated alluvial sediments, shown in blue, lies above bedrock, shown in green.

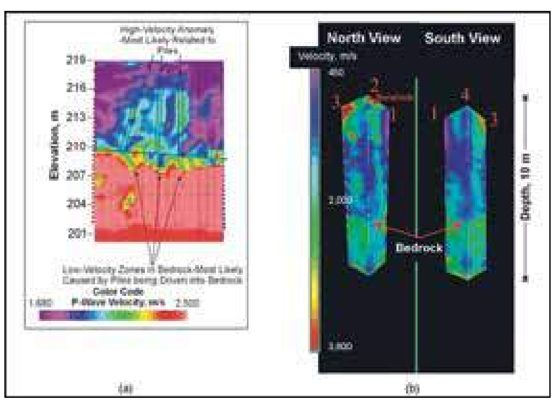


Fig. 76 Tomograms showing: (a) Socketed Piles and (b) Caisson on Top of Bedrock. (NSA Geotechnical Services, Inc. and Blackhawk GeoServices, Inc., respectively)

Advantages: Tomography provides high-resolution two-dimensional area or three-dimensional volumetric imaging of target zones for immediate engineering remediation. Tomography can then be used in before and after surveys for monitoring effectiveness of remediation. Tomography can also be used in before and after surveys for monitoring fluid injections between test holes or for assessing the effectiveness of soil improvement techniques.

Attenuation tomography can be used for the delineating fracture zones. Wave equation processing can be used for a high-resolution imaging of the reflection events in the data including those outside and below the area between the boreholes.

Limitations: Tomography is data-intensive and specialized 3-D analyses software is required for true three-dimensional imaging. Artifacts can be present due to limited ray coverage near the image boundaries.

5.3 monitoring Bridge Deck Conditions

Bridge deck monitoring is an essential component of early stage deterioration detection, whether the deterioration manifests itself through material degradation or defect generation. One of the most common problems in concrete bridge decks is corrosion-induced deck delamination, where expansive corrosion products at the reinforcement level create internal stresses that result in cracking and delamination of the concrete from the reinforcement it is intended to protect. Routine employment of geophysical surveys can yield good results when assessing deck conditions if the proper method(s) are selected.

Bridge deck evaluations can be categorized as initial (QA verification) and baseline condition verification, as well as condition assessment of older, existing structures. Geophysical instruments, including accelerometers and tilt meters, as well as strain gages, are increasingly used for short- and long term monitoring of bridge decks. The basic problems encountered include the aerodynamic stability of bridge decks when subject to high winds, the long-term stability of bridge decks due to fatigue caused by a variety of cyclic stresses including temperature, increased loading from traffic, and heavily loaded trucks and the stability of bridge decks during earthquakes. The primary method used to evaluate stability is to measure the baseline performance characteristics of a structure and then monitor the change in these characteristics with time. This can be done periodically, such as during an inspection cycle, or continuously using a permanent monitoring system. The geophysical techniques applied to this problem are principally vibration monitoring, including strains, displacements, rotations, and accelerations, but also some environmental monitoring including wind and temperature, since these affect the response.

5.3.1 *Ground Penetrating Radar*

Quality Control (QC) is the implementation, measurement, and enforcement of sound construction practices and jobsite inspections to ensure construction quality. Quality Assurance (QA) is the inspection and testing of the completed product, in accordance with specifications intended to verify the quality of the completed structure. In the transportation sector, GPR surveys are routinely and successfully used for quality assurance (QA) verification of new construction. The electromagnetic energy used by the GPR system depends primarily on two physical properties of the ground; the electrical conductivity and the dielectric constant. The dielectric constant determines the speed with which the wave travels and the electrical conductivity determines the attenuation of the electromagnetic signals. Through air, GPR travels at light speed; through another material, its speed is inversely proportional to the square root of its dielectric constant.

Most concrete in-service, has a dielectric of roughly 9 (GPR moves through the medium three times slower than the speed of light), and water slows GPR to only 1/9 its speed in air, because water has the highest dielectric constant (80) of any (dielectric) medium. Asphalt overlays typically have a dielectric constant of about 6 to 6.5. GPR moves faster in asphalt than in most concrete, except when concrete is extremely well cured and dry.

The dielectric contrast—absolute difference in magnitude between two adjacent materials through which a GPR signal will propagate—controls whether there will be a measurable reflection of energy transmitted from the antenna back to the receiver at the surface. The greater the dielectric contrast, the higher the amplitude of this reflection will be. Also, the polarity of the signal will depend on whether the GPR is propagating through a higher, then lower dielectric material or the reverse scenario exists. These and many other subtle GPR signal characteristics help determine accurate depth to rebar, concrete deterioration, overlay thickness, deck thickness, and other structural properties of interest.

Electrical conductivity, the inverse of resistivity, is a property that measures how well a material transports or disperses an electrical current through that given medium. Highly conductive materials, such as metal or seawater, effectively impede all or most of a GPR signal from penetrating them. Similarly, conductive materials that do not fully impede signal penetration, but significantly impair the ability to penetrate them, typically attenuate or disperse the GPR signal so that very little of it can return to the receiver to be measured. Chloride-contaminated concrete is a relatively conductive medium, causing some relative increase in GPR signal amplitude to be measured at a wet surface where chlorides have intruded, and, more importantly, causing a marked decrease in amplitude at the top mat reinforcing level. Much of this amplitude decrease is attributed to greater signal attenuation of the GPR signal through the contaminated concrete, allowing less energy to return and be measured at the surface. These combined conditions are what allow GPR to be effective in identifying conditions that are dominant when rebar is corroding, corrosion products are causing cracking, delamination and spalling, and concrete is otherwise deteriorating.

5.3.2 *Impact Echo*

Impact Echo (IE) test is used to determine deck thickness as well as to evaluate deck de-bonding, corrosion induced delamination and integrity. Impact Echo on bridge decks is done with small metal spheres or electronic solenoid sources. The impact, however it is made, sends acoustic energy into the deck which resonates at a frequency whose wavelength is the thickness of the deck. The frequency spectrum of the receiver is used to determine the depth of reflectors according to:

$$D = V_p/(2 \times f_r)$$

where D is the reflector depth, f_r is the large dominant frequency peak identified in the response, and V_p is the compressional wave velocity.

If the velocity of the concrete is known or can be measured, then the depth of a reflector can be calculated from the reflection echo peak frequency. The wave speed V_p can be measured by observing the travel time of a compressional wave between two transducers held a fixed distance apart on the concrete surface or by performing a calibration test on a slab of known thickness and observing the dominant frequency. The highest amplitude frequency peak is the main indicator of a reflector depth (thickness echo). The presence of additional echo peaks can also be significant, indicating the presence of possible defects or other interfaces in the concrete. The IE technique is thus, used to identify a position of wave reflectors in a bridge deck, detect defects and can be considered as a defect diagnostics tool.

The best use of impact echo on a bridge deck is for overlay thickness. It is necessary to look for sites in between rebar to get the best depth measurement of the deck. Sites affected by the rebar will be readily in the data as a very shallow measurement (at the depth of the rebar). The biggest advantage of the IE method over the current practice of chain dragging is that it allows detection of zones of delamination at various stages: from initial to progressed and developed, thus enabling better prediction of deterioration process in the deck. To improve automation, accuracy and interpretation of results of the IE technique, the testing is simulated by the finite element method in two probable scenarios of delamination progression: expansion/ growth of single small delamination and progressive linking of several smaller delaminations.

5.3.3 *Ultrasonic Seismic Methods and Ultrasonic Surface Waves Methods*

Ultrasonic seismic methods (SASW and MASW) and Ultrasonic Surface Waves Methods are methods for evaluation of material properties and defects in structures based on the generation of elastic waves and measurement of their velocity of propagation and other wave propagation phenomena like reflections, refractions and dispersions. Compression and surface wave velocities are measured and correlated to the elastic moduli and thus, can be described as material quality control techniques. Ultrasonic Seismic and Impact-Echo, particularly when applied together in an integrated instrument such as a Seismic Pavement Analyzer (SPA) or Portable Seismic Pavement Analyzer (PSPA), are high-frequency, acoustic (seismic), geophysical methods for concrete condition assessment. In the transportation sector, these integrated surveys can be used for quality assurance (QA) verification of new construction (thickness determination and homogeneity of concrete pour, even segregation of aggregates or suspected voids) and calculation of mechanical properties, both on bridge decks and pavements. **Fig. 77** shows typical ultrasonic seismic and impact echo test methods.

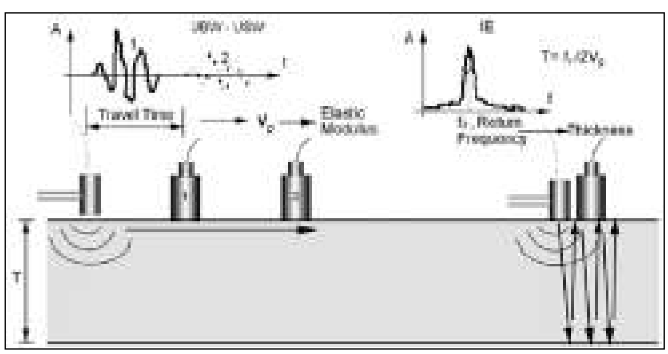


Fig. 77 Typical Ultrasonic Seismic and Impact Echo Test methods

In the first part of the evaluation, the UBW test is conducted using an impact source and two receivers. From the travel time of the P-waves between the two receivers, the P-wave velocity is calculated. Because it is often difficult to identify arrivals of P-waves in an automated way, a more reliable way to estimate P-wave velocity is through the measurement of the R-wave velocity from the USW test. The R-wave velocity, for an assumed Poisson's ratio, can be correlated to both compression and shear wave velocities and thus to the Young's and shear Moduli. In the second part of the evaluation, the IE test is conducted using an impact source and a single nearby receiver. Because of a significant contrast in rigidity of concrete and air the elastic wave is practically entirely being reflected between the bottom and the surface of the deck. The frequency of reflections, called return frequency, is clearly visible in the response spectrum. The depth of the reflector, in this case the deck thickness, can be obtained from the return frequency and previously determined P-wave velocity. In the case of a delaminated deck, reflections of the P-wave occur at shallower depths, causing a shift in the response spectrum towards higher frequencies. **Fig. 78** shows typical portable pavement seismic analyser correlated to initial, moderate and severe delamination development.

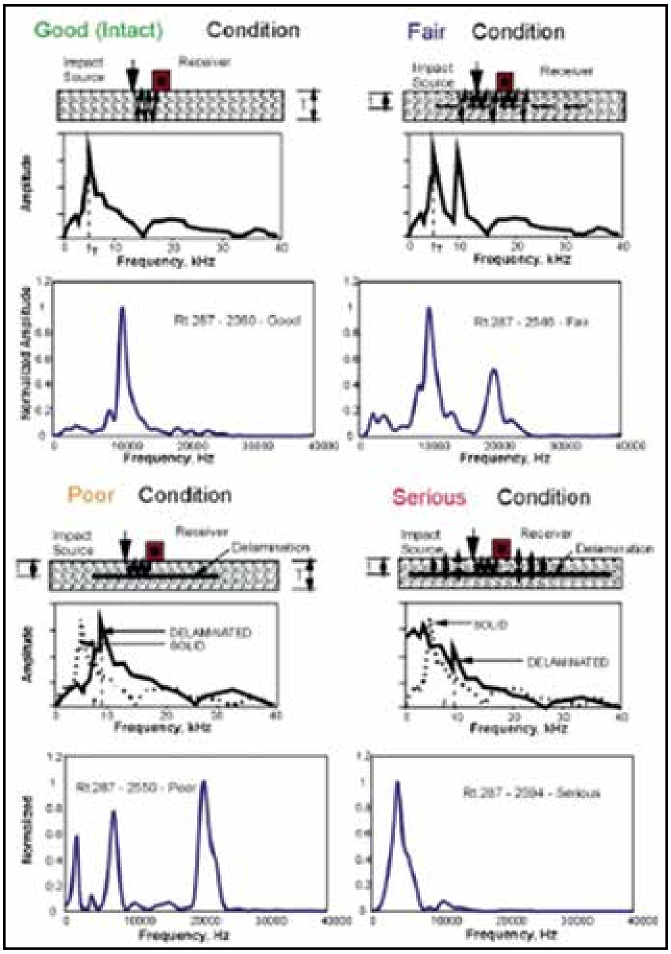


Fig. 78 Typical Portable Pavement Seismic Analyzer (PPSA) correlated to initial, moderate and severe delamination development (fair, poor, serious), respectively

5.3.4 *Pachometer Test*

For baseline condition assessment, the Pachometer, an electromagnetic (EM) instrument sensitive to ferrous content in steel is used to determine cover (depth to reinforcing steel from concrete surface), reinforcement quantity, and layout (spacing of bars and their lateral positions within the deck). It is best used to locate reinforcement in (a) rehabilitation situations where cutting or coring into concrete does not involve the risk of damaging post-tensioned cables and ducts, electrical conduits, fiber-optic conduits, or other embedded utilities; and (b) structural analysis calculations where reinforcing is known to be spaced at fairly large and consistent intervals within the depth range that these instruments are suitably sensitive.

5.3.5 *Infrared Thermography*

Imaging using infrared thermography is a nondestructive geophysical approach used with some degree of accuracy when evaluating the condition of existing bridge decks, specifically for detection of shallow delaminations in bare concrete decks or identification of de-bonded zones at an overlay/deck interface. IR thermography identifies delaminations and de-bonded areas because it is sensitive to heat differences at the deck surface caused by the uneven rates of warming and cooling (accumulation and dissipation of thermal energy) between mass concrete, air-filled cavities (delaminations or de-bonded areas), and water-filled delaminations or de-bonded areas. Temperature differences on the surface can indicate the location of usually shallow delamination. Its primary limitations are:

i) Unreliability of solar heating to provide even thermal energy input into all areas of the deck.

ii) Speed of survey is limited to about 3 to 5 km/h, meaning that deck condition (thermal gradient) can change considerably from start to end of the survey, and a very slow-moving “mobile lane closure” is required.

iii) Effect of shadows from trusses, cables, walls, jersey barriers, and/or overhead decks generally ensure that uneven thermal loading and dissipation are taking place, removing much of the objectivity of the analysis.

iv) Dissipation of heat at a rapid rate by a mild breeze, particularly if the wind is sporadic with large variations in intensity; heat is removed temporarily at the surface on actual “hot-spots” that are missed as the survey progresses.

v) Problems with variations in reflectance from surface materials or surface conditions that can confuse or otherwise complicate the interpretation, such as pavement patches, surface staining from oil or burned pavement, surface ‘polishing’ of a concrete deck or asphalt overlay, light and dark areas on a deck caused by sunlight and shadow, pavement markings (paint), etc.

vi) Time limitations brought about because surveys typically must be performed at limited times of the day when conditions are favorable, i.e., a few hours after initial warming of the deck when heat-retention differences at the surface reveal defects (morning hours) or immediately at or after sundown, when deck surfaces rapidly cool in some areas and more slowly cool in others.

5.3.6 *Ultrasonic Pulse Velocity (UPV) Test*

UPV method is used for computing the ultrasonic pulse velocity of structural concrete. UPV can be used for assessing integrity of structural concrete elements of up to 7.5 m thick with two-sided access. This technique involves measuring the travel time of acoustic pulses through material with a known thickness. The frequencies of the transmitted signals vary from 50 to 300 kHz. Under certain conditions, it is possible to estimate the compressive strength using the ultrasonic pulse velocity method. The method requires that objects to be tested have two sides available for access. Voids, honeycomb, cracks, delaminations, and other damage to concrete can be located. This method is used to predict the strength of early stage concrete and as a relative indication of concrete quality. **Fig. 79** shows typical relation between pulse velocity and compressive strength.

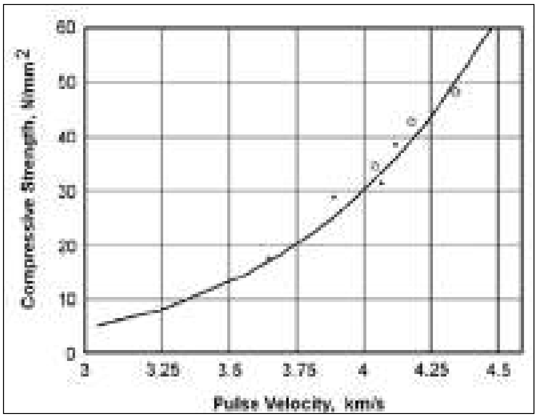


Fig. 79 Typical Relation between Pulse Velocity and Compressive Strength

6 INTEGRATING GEOPHYSICAL mETHODS

Planning for geophysical survey should be considered from the inception of a project, and the potential information that geophysical data may offer should be anticipated. Planning of a hypothetical project might anticipate the following stages:

i) Define research goals
ii) Site reconnaissance
iii) Assess feasibility
iv) Develop appropriate survey design
v) Conduct survey
vi) Develop preliminary interpretations
vii) Ground truthing (on-the-ground testing)
viii) Refine interpretations

As explained in the earlier sections, different methods have their individual limitations. As an example, seismic refraction is an excellent tool for obtaining information on rock depth, but suffers from the limitation that velocity must increase with depth. In few typical geological conditions, the assumptions does not hold good, and in such cases electrical tomography provides an excellent complimentary tool.

Another good example is importance of shear wave velocities. The P-wave velocity in a material is mostly dependent on compressive strength. Experience (with a little common sense and some helpful tables) allows us to guess something about the material once the velocity is known. For example, if the P-wave velocity is 600 m/s, then we know that the material is probably a compacted soil. A sudden increase to 1500 m/s suggests that we have hit the water table. A velocity above 3000 m/s is almost certainly a fairly competent bed rock. A refraction analysis will tell us the depth from the surface to each of these materials and this result is adequate for many applications such as finding the depth to ground water or the excavation costs. However for major applications, like nuclear power plants, the complexity is much more. For a payer with velocity of 1500 m/s, no longer can we assume that this is just a saturated alluvial material. Consider some of the materials that might exhibit this same compressional wave velocity: saturated gravels, clay deposits, weathered rock, coal, or even quick sand. The shear wave velocities of these material show wide variations and help us uniquely resolve the problem.

7 REFERENCES

1. Elias, V.A., "Strategies for Managing Unknown Bridge Foundations", FHWA-RD092-030 report, Washington, D.C., January 1992.
2. Olson, L.D., Wright, C.C., "Nondestructive Testing of Deep Foundations with Sonic Methods", Proceedings, ASCE Geotechnical and Construction Divisions Specialty Conference, Northwestern University, Evanston, Illinois, 1989.
3. Duke, S.K., "Calibration of Ground Penetrating Radar and Calculation of Attenuationand Dielectric Permittivity Versus Depth", Master's Thesis# T-3920, Colorado Schoolof Mines, Golden, Co, (1990), 236 pp.
4. Haeni, F.P., Placzek, G., Trent, R.E., "Use of Ground Penetrating Radar to Investigate Refilled Scour Holes at Bridge Foundations", Geophysical Survey of Finland, Special Paper 16, (1992), pp. 285-292.
5. Pratt, D., and Sansalone, M., "Impact Echo Interpretation Using Artificial Intelligence," ACI Materials Journal, Vol. 89, No. 2, (1992), pp. 178-187.
6. Dunscomb, M.H. and Rehwoldt, E. (1999), "Two-Dimensional Profiling; Geophysical Weapon of Choice in Karst Terrain for Engineering Applications," Hydrogeology and Engineering Geology of Sinkholes and Karst – 1999, Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Hershey, Pennsylvania, April 10-14, pp. 219- 224.
7. Geophysical Survey Methods Used at Site Investigations at Radford Army Ammunition Plant (RFAAP)
8. Benson, Richard C., An overview of geophysical and non-destructive methods for characterization of roads and bridges
9. Soil engineering for the Technician. Downloaded from ascelibrary.org
10. Michael L. Rucker, P.E., Surface geophysics as tools for characterizing existing bridge foundation and scour conditions
11. Foundation report preparation for bridges by division of engineering services & geotechnical services
12. Geotechnical Engineering Notebook by the Federal Highway Administration, U.S Department of Transportation
13. Hiltunen, Dennis R. and Roth, Mary J.S., Investigation of bridge foundation sites in karst terrane via multi-electrode electrical resistivity
14. Delineation of Tidal Scour through Marine Geophysical Techniques at Sloop Channel and Goose Creek Bridges, Jones Beach State Park, Long Island, New York by the USGS (Water-Resources Investigations Report 00-4033)
15. Jean-Louis Briaud, Zenon Medina-Cetina, Stefan Hurlebaus, Mark Everett, Stacey Tucker, Negin Yousefpour, and Rungroj Arjwech, Unknown foundation determination for scour.
16. L.J. Prendergast, K. Gavin, A review of bridge scour monitoring techniques, Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 138-149.
17. Application of geophysical methods to Highway-related problems, September 2003, Central Federal Lands Highway Division, U.S Department of Transportation. Federal Highways, Publication No. FHMA-IF-04-021 of August 2004.
18. Cardimona, S., B. Willeford, J. Wenzlick and N. Anderson, "Investigation of Bridgedecks Utilizing Ground Penetrating Radar," International Conference on the Application of Geophysical Technologies to Planning, Design, Construction, and Maintenance of Transportation Facilities, St. Louis, MO, in press, 2000.
19. John Hema, E.I.T, W. Spencer Guthrie, Ph.D. and Fernando S. Fonseca, Ph.D., P.E., Concrete bridge deck condition assessment and improvement strategies.

(The Official amendments to this document would be published by the IRC in its periodical, 'Indian Highways' which shall be considered as effective and as part of the Code/Guidelines/Manual, etc. from the date specified therein)