COMPARATIVE STUDY OF SHEAR WAVE VELOCITY USING FIELD AND LABORATORY TESTS

A DISSERTATION

Submitted in the partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

EARTHQUAKE ENGINEERING

(With specialization in Soil Dynamics)

by

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JUNE, 2019

CANDIDATE'S DECLARATION

I hereby, declare that the work which is being presented in this dissertation report entitled, **"COMPARATIVE STUDY OF SHEAR WAVE VELOCITY USING MASW AND BENDER ELEMENT TESTS"**, being submitted in partial fulfilment of the requirements for the award of degree of "Master of Technology" in "Earthquake Engineering" with specialization in Soil Dynamics, to the Department of Earthquake Engineering, Indian Institute of Technology Roorkee, under the supervision of Prof. B.K. Maheshwari, Department of Earthquake Engineering, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out during the period of June 2018 to June 2019.

Place: Roorkee **Vatan Sharma**

Date: Enrollment no. 17525010

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Place: Roorkee **(Dr. B.K. Maheshwari)**

Date: Professor

Department of Earthquake Engineering

Indian Institute of Technology Roorkee

ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude and indebtedness to my guide and mentor **Dr. B.K. Maheshwari**, Professor, IIT Roorkee for being helpful and great source of inspiration. I am thankful to him for his persistent interest, constant encouragement, vigilant supervision and critical evaluation. His encouraging attitude has always been a source of inspiration for me. His helping nature, valuable suggestions and scholastic guidance are culminated in the form of the present work.

I would like to record my deep sense of gratitude to my encouraging parents and my loving sister, and my family, without whose blessings and love the thesis would not have seen the daylight. I would also like to thank all my dear friends and classmates for their support.

I express my gratitude to my seniors **Ms. Aparna Kanth, Mr. Sukanta Das** and **Mr. Mohd Firoj** for their sincere support and help during the process of this research work. The help and the support extended by staff of Soil Dynamics Laboratory of Earthquake Engineering Department, during the experimental investigation is gratefully acknowledged. Particularly **Mr. Subodh Jain**, (Technical Supt.) I am thankful to other staff of Lab i.e. **Mr. Prem Chand** for their help during arrangement of test setups and testing process.

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ABSTRACT

A comparative study of shear wave velocity between field and laboratory tests has been proposed in the present study. The bender element test was adopted for laboratory test while MASW and SPT tests for field measurement for shear wave velocity. In MASW seismic waves is created through hammering and the velocities of these waves analysed and then finally the shear wave velocity (V_s) with the depth is deduced. In Bender Element, both transmitter and receiver of shear wave is used.

The shear wave velocity has been investigated at the shallow depth for four different sites i.e. Solani riverbed, Bahadrabad, Haridwar and Bhagwanpur within Roorkee-Haridwar region. Samples from different depths have been collected using SPT and tested using Bender Element. Also SPT N-value is recoded. This has been done by Kirar (2016) and data from that study is used here. While MASW is conducted on the same sites to determine the shear wave velocity. In this work, the shear wave velocity (V_s) using SPT, MASW and Bender Element are compared and analysed. A regression analysis has been carried out to establish a correlation between field and laboratory shear wave.

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Chapter-1

INTRODUCTION

1.1 General

Geophysical investigation use is increase nowadays in civil engineering terms to determine the subsurface characterization. There are several applications of these investigation depends on the methods used. In civil engineering, the most common method is seismic technique to evaluate the subsurface layering of the ground using seismic waves. The application of the seismic techniques is geologic layering, bedrock depth, landfill investigations, rock properties, water table etc. In past, the subsurface assessment is majorly done by the conventional methods like SPT (Standard Penetration test), CPT (cone penetration test) and DCPT (Dynamic cone penetration test). But geophysical methods have some advantages over these conventional methods. Firstly, geophysical methods are mostly non-destructive methods so this cause no disturbances to the original soil strata. Secondly, geophysical instrument generally is light in weight and the time of testing to extract the information is very less compared to the other conventional methods. Therefore, the cost of the labour in geophysical methods is also less compared to the other orthodox methods. There is an another advantage of geophysical method over previous method is that it also collects the data of the hard stratum at which borehole is not possible. The geophysical methods have some disadvantages also these methods have high uncertainty in its results.

In early 2000 the MASW (Multichannel analysis of surface wave) test becomes popular among geotechnical use. The MASW word originates from a publication made on geophysics (Park et al. 1999). The project actually started in the mid-90s by the geophysicists of the Kansas Geological Survey (KGS). These geophysicists previously used seismic reflection method in the oil industry to explore the interior part of the earth up to several kilometres. In the mid-90s KGS shifted their goals to the geotechnical projects.to investigates the sub surface properties up to 100m. From the extensive studies performed by SASW they know that the surface wave studies are more complex so it is very difficult for two receivers to handle that complication. So they developed new strategies in data collection and processing to detailed the surface wave propagation. Presently there are various empirical correlation between Vs (shear velocity) using MASW and SPT (Standard penetration Test) N-values had been developed for the different regions of India as well as for the world. The empirical relation between Vs and N-value for the sandy soils are given by some researchers (Shibhita, 1970; Ohta et al., 1972; Okamoto et al., 1989). The several research also published in which the correlation has been developed between Vs and N-values for the clay (Lee, 1990; Athanasopoulos, 1995; Dikmen, 2009). In Roorkee-Haridwar study region an empirical relation between Vs and N-value previously developed by the researcher (Kirar et al. (2016)). MASW method success majorly depends on the specific site condition and the accurate result interpretation. In addition to that MASW does not consider variation of various parameters confining stress, shear strain and loading frequency. All of these limitation overcomes in the laboratory testing like cyclic triaxial, resonant column, bender element etc. In this study bender element is a major concern to determine shear wave velocity. Bender element was introduced to the geotechnical application by Shirley and Hampton (1978). It gains popularity because of its simplicity and cost effectiveness. One of the major concern in using the bender element that the results are not consistent with the other methods like resonant column. The important reason for the unmatched result is the signal interpretation of the shear wave velocity is very tough problem. The signal interpretation is always being a tricky problem because of the near field effect. The different interpretation method may give fluctuation in the results (Greening and Nash, 2004; Yamashita et al., 2009).

In this study the major focus is to do comparative study of the shear wave velocity using both laboratory and field tests. MASW is used for the in-situ testing while Bender Element incorporated in cyclic triaxial is used for the laboratory testing to determine the shear wave velocity. SPT (Standard Penetration Test) is also used for the sample collection and N-value of the site. N-values data helps to find out the absurd result obtained from both the MASW and the Bender Element. An empirical relation has been developed between shear velocity obtained from laboratory and field tests. There are so many benefits of this study are the cost of doing complete set of testing includes bore hole testing and laboratory testing is very much expensive. So by using these correlations there is need to do either in-situ or laboratory testing which reduce the costing of whole procedure. Secondly, if there is space restriction to do detailed in-situ testing so these type of correlation will be use to evaluate the result directly.

1.2 Objectives of Dissertation

The primary objective of this study is to examine the shear velocity of ground at different sites of Roorkee-Haridwar region and compare the shear velocity between laboratory and field tests for shallow depth of ground. For this, following tasks will be carried out:

1. Find the insitu shear velocity using MASW tests at four different sites i.e. Solani riverbed site, Bahadrabad site, Bhagwanpur site and Haridwar site of Roorkee-Haridwar region.
2. Extract the data of Standard Penetration test of the same sites from Kirar (2016) for determination of shear wave velocity using N value.
3. Report the data regarding index soil properties and grain size distribution at different depth of ground from Kirar (2016) for all four sites.
4. Extract the Bender Element test data regarding shear modulus from Kirar (2016) to find out shear velocity.

Normally MASW gives constant value of shear wave velocity (V_s) with dpth for certain intervals of depths. To resolve this, the results obtained from MASW are compared with those obtained from SPT and Bender Element tests. An equation is derived correlating shear wave velocity using MASW and Bender Element tests.

1.3 Organization of Report

The report comprises of 5 chapters.

Chapter 1 presents introduction and the general work plan of the report.

Chapter 2 presents brief description of literature review of experimental work

Chapter 3 provides details about the test setup and its procedure

Chapter 4 provide test analysis and result

Chapter 5 comprises of summary and references.

Chapter-2

LITERATURE REVIEW

This chapter includes the information and review of studies done in past on dynamic soil properties using MASW and Bender element.

The evaluation of shear velocity of soils has significance for many engineering problems such as caused by earthquake. The response of the soil is controlled by its basic properties; particularly those which easily gets affected by wave propagation effects, only low level of strains is induced. Hence behaviour which are subjected to dynamic loading is influenced by its dynamic properties

2.1 Past Studies using MASW

Park et al. (1999) Site characterization regarding shallow subsurface is generally done by Rayleigh waves dependent property. Source distance and its related frequency is generally the important parameter in the estimation of shear wave velocity. In seismic survey investigation it is found out that two third of two third of seismic energy generates Rayleigh waves. Different frequency component in surface wave has different propagating velocity.

Mitttal et al. (2012) categorize sites based on physical interpretation of shallow surface constituents and average shear velocity for the 30 m (V_{s30}). In this study majorly there is distinguish between the rock and soil. The whole classification was done by estimating the physical properties of the upper part of the ground strata. The major objective of this study was to classify a group of strong motion stations into several classes using SMA (strong motion accelographs). These type of classification helpful to the engineers to understand site condition by its class. According to shear wave velocity the earth internal structure is classified as shown in Table 2.1.

Table 2.1 Site class for SMA station (After Mittal et al., 2012)

Class	Site Type	V_s
A	Firm or hard rocks	>700 m/sec
B	Soft to firm rocks	375-700 m/sec
C	Soils	<375 m/sec

Pandey et al. (2016a) observed strong ground motion and includes hazard related studies for the India capital city Delhi. In this region soil thickness and its properties varies significantly at regular interval. In this study site characterization is done with MASW tests for different sites of Delhi region. The site classification of site condition according to the NEHRP (National Earthquake Hazards Reduction Program) is given in the Table 2.2 (Building Seismic Safety Council, 1999). In addition to that some detailed ground analysis is also conducted using STRATA software to found out the results of local site effects regarding the strong ground motion.

Table 2.2 Classification of sites based on V_{s30} (NEHRP)

Site Class	**Site Condition**	**Shear wave velocity V_{s30}** (m/sec)
A	Hard Rock	>1500
B	Rock	760-1500
C	Very dense soil and soft rock	360-760
D	Stiff soil	180-360
E	Soft Soil	<180

Table 2.3 Showing V_{s30} and NEHRP site class for Delhi region (After Pandey et al. 2016a)

S.No.	**Site Name**	**V_{s30} (m/sec)**	**NEHRP Site Class**
1.	GEC Jaffarpur	338	D
2.	Jamia	346	D
3.	Kalkaji	564	C
4.	Vikaspuri	360	D
5.	IMD Ridge	543	C
6.	NPTI Badarpur	322	D
7.	JNU	565	C
8.	Shivaji College	346	D

Pandey et al. (2016b) observed strong ground motion and includes hazard related studies for the Tarai region of the Uttrakhand. In this study site characterization is done with MASW tests for different sites of Tarai region. The V_{s30} and its site class according to NEHRP is shown in Table 2.3. In addition to that some detailed ground analysis is also conducted using

STRATA software to found out the results of local site effects regarding the strong ground motion.

Table 2.4 Showing V_{s30} and NEHRP site class for Delhi region (After Pandey et al. 2016b)

S.No.	Location	V_{s30} (m/sec)	NEHRP Site class
1.	Tanakpur	434	C
2.	Khatima	218	D
3.	Udham Singh nagar	198	D
4.	Kashipur	208	D
5.	Haridwar	294	D
6.	Kotdwar	448	C
7.	Roorkee	218	D
8.	Haldwani	472	C
9.	Rishikesh	305	D
10.	Vikasnagar	425	C
11.	Dehradun	289	D
12.	Laksar	187	D

2.2 Past Studies using Bender Element

Bender element basically a laboratory test to determine the shear wave velocity. By using shear wave velocity, we determine G_{max} of the soil also. G_{max} is helpful in determining other properties which influence the site condition for ground motion in case of Earthquake.

Kumar and Madhusudhan (2010) In this study the bender and extender elements are used to measure the travel time of Primary and shear wave for dry sample at different confining pressure and relative densities. Three methods of interpretations of travel time were used:

- The first time of arrival
- The first peak to peak
- The cross-correlation method

The all three methods give approximate same value for the P-wave travel time measurements. But there was a variation observed in the arrival time of shear wave velocity.

Cherian and Kumar, (2015) Bender element and Extender element are used to evaluate the waves velocity i.e**.** P-wave and S-wave usually by the several geotechnical researchers. In this study measurement of the arrival time of both P- and S- wave is taken in account. For this purpose, author performed several tests at different frequencies between 1 and 10 taken dry sand as a sample, for different confining pressure and relative density. In this research arrival time of both P - and S- wave evaluated with two corrections.

- The presence of an initial offset in the input signal
- A time delay between the input and receiver signals when the two elements are kept in direct contact with each other.

In this study there is comparison between first time wave arrival method and first peak to peak method for the arrival of the P- and S- wave.

Kirar (2016) In this study bender element was conducted to find out the shear modulus on the sample collected at the different depths from the SPT for the four sites of Roorkee-Haridwar region (Solani Riverbed site, Bahadrabad site, Bhagwanpur site and Haridwar site). The data regarding shear modulus is used here to deduce the shear velocity for the same sites.

Chapter-3

EXPERIMENTAL SET UP AND TEST PROCEDURE

3.1 Field tests

Properties of the in situ soils are measured to obtain their existing stress conditions. Field tests in the present work include Standard Penetration Test (SPT) and Multichannel Analysis of Surface Wave (MASW). Both are described in following sections.

3.1.1 Standard Penetration Test

This test is performed in the field according to the specification given in IS: 2131 (1997). The sampler is used in the SPT test is the standard split-spoon sampler. First the bore hole is advanced to the desired depth at which N-value is to be calculated, then used drilling tools is removed from the bore hole and the sampler is lowered to the level of the bore hole. The sampler is allowed to penetrate into the soil for depth of 450 mm impact loading using drop hammer of 63.5 kg having free fall of height of 750 mm with rate of 30 to 40 blows per minute. But the number of blows for first 150 mm penetration of sampler is not noted because there is a possibility of the loose materials or cuttings deposit in the first drilling operation. The number of blows for the next 300 mm is recoded and it gives the N-value at that depth. The sample is collected from split barrel of the split spoon sampler. The collected sample is send to the laboratory in air tight packets to preserve the moisture content and for the other laboratory test. The next stage of testing is 750mm from the previous level. If the bore hole depth is large than interval of the next stage of testing is increased to 1.5m to 2.5m or at the change of strata. If it is not possible to drive the sampler for the 450mm in case of boulder and rock than N-value is taken for the first 300 mm. The conditions for the refusal of the test at certain point (Ranjan and Rao, 2000).

- 50 blows for 150mm penetration
- 100 blows for 300mm penetration
- No penetration for the 10 blows

The complete setup of the SPT apparatus is shown in Fig. 3.1 There are some precaution which have to be taken in account to conduct SPT test.

- free fall height must be 750 mm it should be frictionless and vertical.
- For the collection of the undisturbed sample bore hole bottom should be cleaned.

- When testing is done below the ground water table in the sandy soil than to prevent the quick sand condition depth of water table should be greater than ground water table.

Soil is classified according to the N values for both sandy and clayey soil (Ranjan and Rao, 2000)

Table 3.1 N Values for Cohesionless Soils (After Ranjan and Rao, 2000)

N value	Description
< 4	Very loose
4 - 10	Loose
10 - 30	Medium
30 - 50	Dense
>50	Very Dense

Table 3.2 N Values for Cohesive Soils (After Ranjan and Rao, 2000)

N value	Description
<2	Very soft
2-4	Soft
4-8	Medium
8-16	Stiff
16-32	Very Stiff
>32	Hard

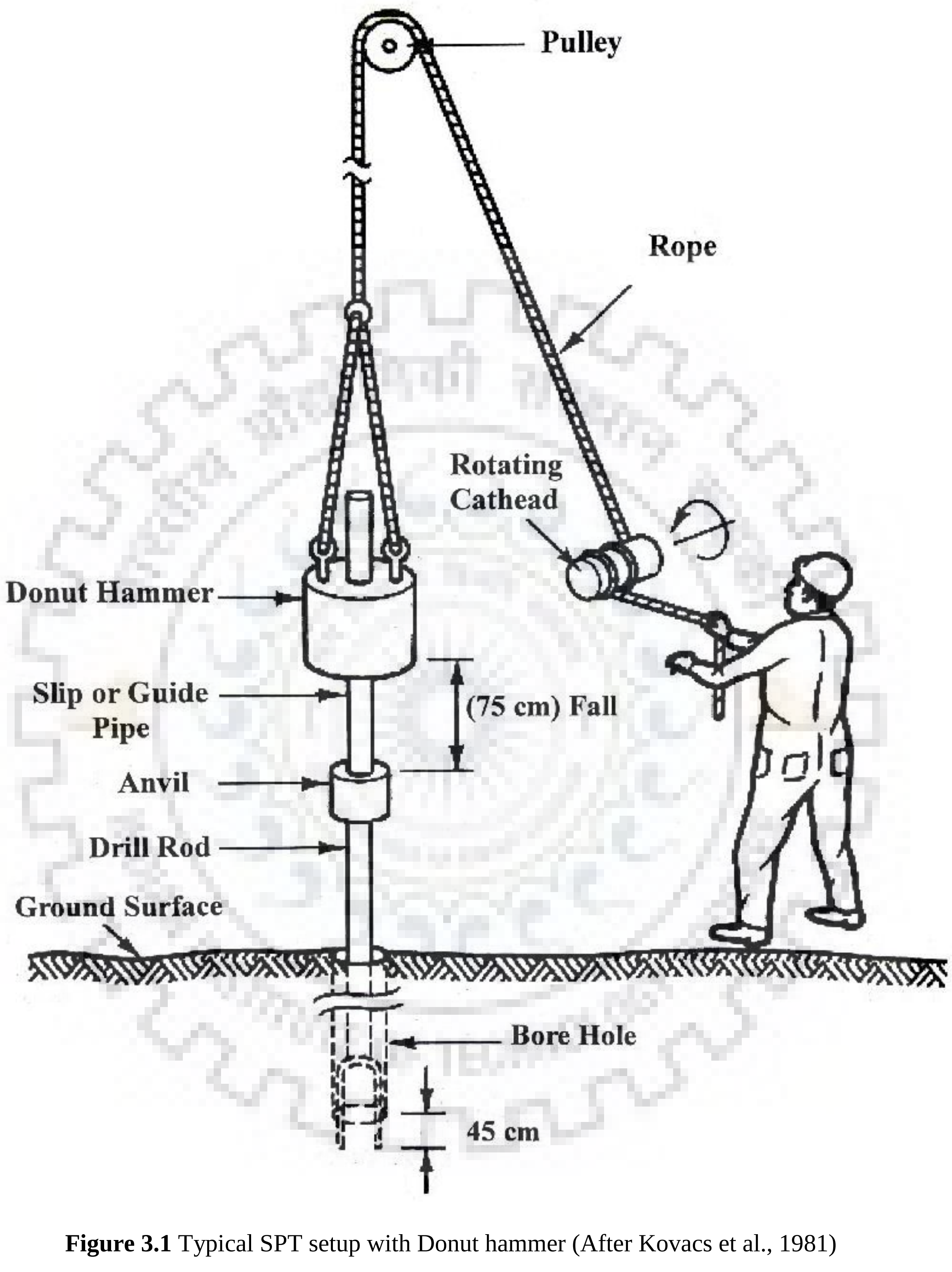


Figure 3.1 Typical SPT setup with Donut hammer (After Kovacs et al., 1981)

3.1.2 MASW Test

Description of Test Apparatus: MASW is multichannel digital system for active and passive seismic estimation. Several number of unique features made it a very special seismograph. Geophysical investigation for the shallow depth of soil generally conduct by MASW instrument (Soil spy) to evaluate shear wave velocity. This instrument does not sufficient to determine the Vs for the deep strata. The MASW was firstly introduced in 90s for evaluating the shear wave Park et al., (1999). MASW test for the estimation of the shear wave velocity sketch for the soil strata is categorized into three following steps.

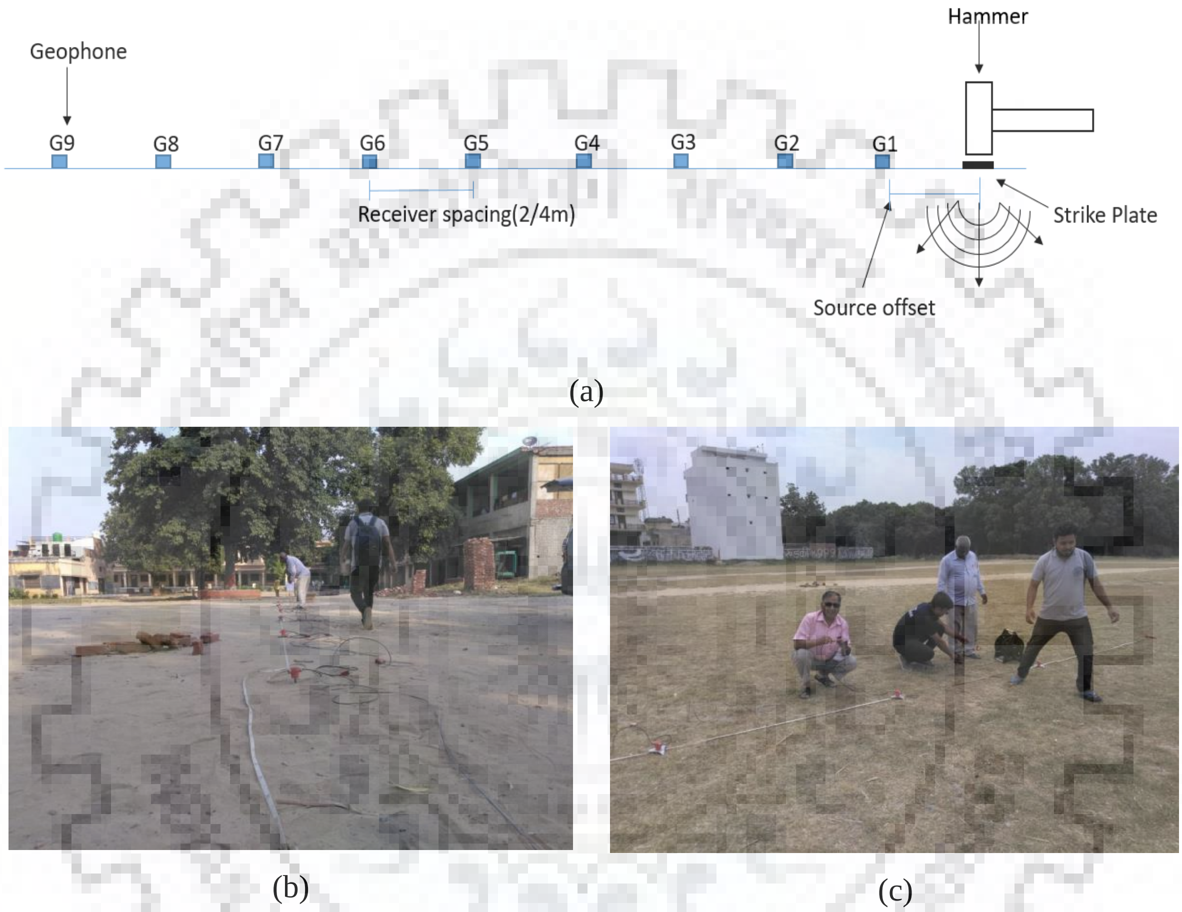
- Field Measurements
- Data Processing
- Inversion analysis

Field Measurements: There are several similar geophones are used in a straight line and having equal spacing for active source (impact source is used) of testing on the test site. By using hammer (active source) wave was generates at the starting end of lined geophones. The wave travel from one end to the other end and geophones receives these waves irrespective of the direction. These phenomena obtain a wave travelling motion as a function of time. The details about geophone, software, mode of conduct is given below

- Soil Spy Rosina is the software combines with the hardware digitally for the estimation of the both type of the surveys i.e. active and passive
- The setup consists of the 9 sensors (geophone) with 2-4 m (depend on the survey) spacing between them. The sampling rate and dynamic range for sensor is 89 kHz and 142dB respectively. The nearest one from the source is used as a trigger.
- Soil Spy software allows to set the parameters, check the recordings, and pre-process data. Dispersion curve can be assimilated in two different modes of active source testing: (1) continuous mode and (2) trigger mode (fixed duration recording).
- In this study, we recorded only fixed duration stacked data to attain finest possible dispersion curve

Data Processing: Grilla is the software to analyse the recorded data from Soil Spy Rosina in the field. The different module of this software helps in making dispersion curves from Soil Spy Rosina recorded data. The generated dispersion gives good result for the shallow depth regarding shear velocity.

Inversion Analysis: An iteration analysis is done between shear wave velocity and the thickness of the soil for layered strata to creates a theoretical dispersion curve which fits the original experimental dispersion curve up to certain frequency is reserved as a result of survey. For the iteration analysis the curve used as a reference is the experimental one to determine theoretical curve (Park et al., 1999).



(a)

(b) (c)

Figure 3.2 (a) Line diagram of Soil Spy Multichannel Seismograph (b)MASW setup at Bahadrabad site &(c) MASW setup at Bhagwanpur site

3.2 Laboratory Tests

Testing of quality undisturbed samples (Kramer 1996) is very important parameter to estimate dynamic properties of the soil. However, it is always difficult to extract quality undisturbed samples. For the sandy soil it is almost impossible to extract undisturbed sample so majorly testing on sandy soil is done on remoulded samples. In laboratory tests are performed on small scaled model is tested which represent the actual larger body of soil. In present study, the soil specimens are tested with proper initial stress or strain conditions. In present study, bender element test is considered for determination of shear velocity of soils.

However, before determination of shear velocity it is always necessary to classify the soils on the basis of their index properties, therefore index properties tests are also conducted on all the samples.

3.2.1 Tests for Index Properties

The laboratory tests are conducted on all the samples collected to find out the required index properties (Kirar 2016).

(a) Grain size distribution: represent the particle size based distribution of the soil mass of different particle size. Sieve analysis (IS: 2720 Part4-1983) is done to determine the Grain size determination. Than plot the percentage finer (in %) vs particle size (logarithmic scale).

From the grain size distribution curve determine the co-efficient of uniformity (C_u)

$$C_u = D_{60} / D_{10} \tag{3.1}$$

Where,

D_{60} = particle size such that 60% of the particles are finer than this size

D_{10} = particle size such that 10% of the particles are finer than this size

The general shape of the grain size distribution curve is described by coefficient of curvature (C_c) given by

$$C_c = (D_{30})^2 / (D_{60} * D_{10}) \tag{3.2}$$

Where D_{30} is the particle size corresponds to 30% finer

(b) Relative Density: It is an important property of granular material and defined as

$$D_r = (e_{max} - e) / (e_{max} - e_{min}) \tag{3.3}$$

Where, D_r is the relative density, e_{max} is the maximum void ratio, e_{min} is the minimum void ratio (IS: 2720 Part 14 - 1986) and e is the natural void ratio

(c) Specific gravity: The G (specific gravity) of solid particles is determined by pycnometer method (IS: 2720 Part 3-1980).

(d) Atterberg Limits: The liquid limit of soil is determined by Casagrande tool (IS: 2720 Part 5-1965).

Plastic Limit (PL) is the moisture content at which a soil just begins to crumble when rolled into a thread of (3mm) diameter using a ground glass plate (IS: 2720 Part 5-1985).

Plasticity Index (PI) of a soil is the difference between liquid limit and its plastic limit

3.2.2 Bender Element

In laboratory, the determining of shear wave velocity has been done by Bender Element. Piezoelectric element has been incorporated into cyclic triaxial device. Bender elements are assembled by joining two piezoelectric plate together to bend the entire element in case of voltage applied to their faces because that cause contraction and expansion of the opposite faces. Similarly, a voltage is produced when there is a disturbance in a Bender Element therefore it can be used as transmitter and receivers both of s-wave. A voltage pulse is input in the Bender Element to the transmitter piezoelectric plate cause s-wave (in the form of Sine wave). When the wave reaches the other end of the specimen that cause distortion of the receiver element which produces another voltage pulse.

The time difference (t_o) of these two voltage pulses has been measured with oscilloscope and shear wave velocity (V_s) is calculated as

$$Vs = L_{tt} / t_o \tag{3.4}$$

Where, L_{tt} = tip to tip distance between transmitter and receiver

Shear modulus can also be determined of soil sample by the Bender Element. After the determining of shear wave velocity, the maximum shear modulus (G_{max}) can easily calculated by the following equation (Kumar and Madhusudhan, 2010)

$$G_{max} = \rho * V_s^2 \tag{3.5}$$

Where, ρ - mass density of the specimen, V_s – shear velocity

There are number of methods of for determining the travel time of the shear waves in the soil sample, based on the transmitted and received signals. One approach which is commonly used for the determine shear velocity is by visual picking. In this method the time of first major deflection of received signal is booked as the arrival time of the shear velocity. This method gets popularity because it is very easy and straightforward. The first significant deflection from zero amplitude might be positive or negative.

Chapter-4

SHEAR WAVE VELOCITY USING DIFFERENT TECHNIQUES

4.1 Sites Location

In the present study, four site has been chosen within Roorkee-Haridwar region. The latitude and longitude are given in Table no. 4.1.

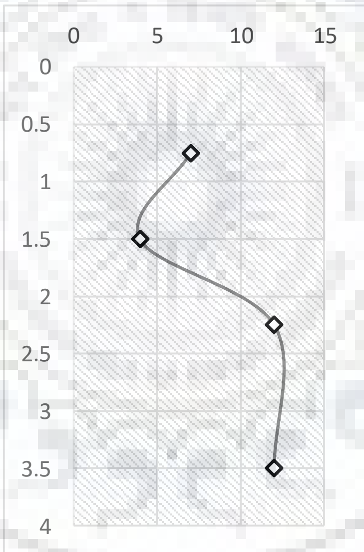
Figure 4.1 Satellite view of all sites

Table 4.1 Sites location

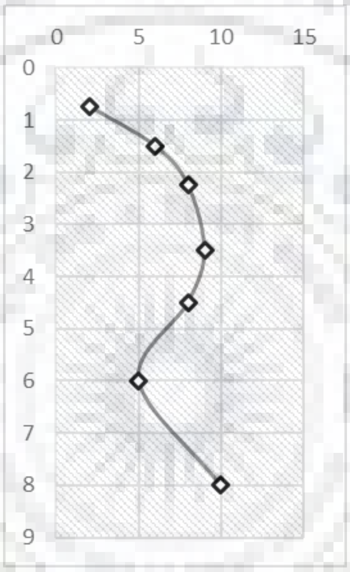
S.No.	Test Sites	Latitude	Longitude
1	Solani Riverbed	N29^0 52.907’	E77^0 53.965’
2	Bhagwanpur	N29^0 56.203’	E77^0 48.820’
3	Bahadrabad	N29^0 55.087’	E78^0 02.307’
4	Haridwar	N29^0 59.420’	E78^0 09.019

4.2 Bore Hole Data

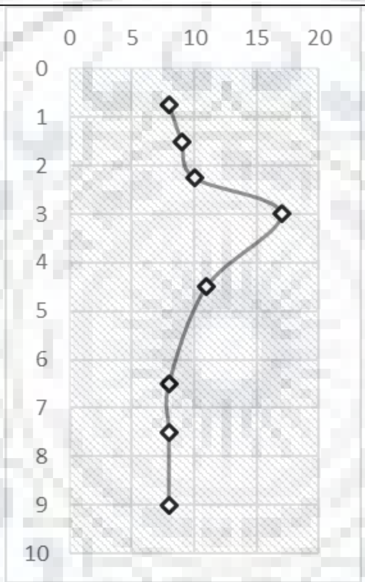
In this section, the bore hole data of all the four sites are shown which is taken from Kirar (2016). The solani riverbed site is near Solanipuram, Roorkee. It is about 3 km from IIT Roorkee campus. SPT was conducted and the bore hole was 50 m apart from Aquaduct. The bore hole depth was 3.5 m at that site. The water table was found at 2 m from the ground surface.

<table>
<tr><td colspan="5">Bore Hole: 1</td></tr>
<tr><td colspan="5">Location: Solani Riverbed Site</td></tr>
<tr><td colspan="5">Depth of water table: 2 m</td></tr>
<tr><td colspan="5">Bore Hole depth: 3.5</td></tr>
<tr><td>Depth(m)</td><td>Soil Type</td><td>N-value</td><td>Fine content</td><td>Specific Gravity</td></tr>
<tr><td>0.75</td><td>SP</td><td rowspan="4">
</td><td rowspan="4">2.6-3%</td><td>2.64</td></tr>
<tr><td>1.50</td><td>SP</td><td>2.65</td></tr>
<tr><td>2.25</td><td>SP</td><td>2.63</td></tr>
<tr><td>3.5</td><td>SP</td><td>2.66</td></tr>
</table>

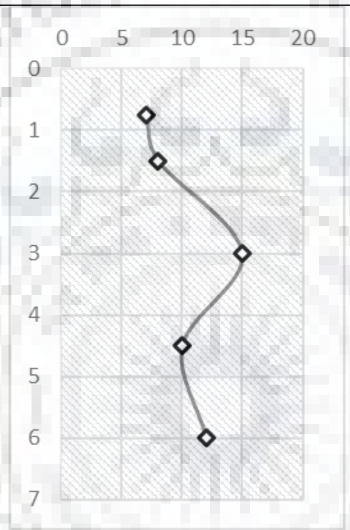
The Bhagwanpur site is situated on NH 73 which is about 15 km from Roorkee. The SPT was conducted in the ground near Government Inter College. The bore hole depth was 8 m at that site. The water table was found at 2.5 m from the ground surface

<table>
<tr><td colspan="5">Bore Hole: 2</td></tr>
<tr><td colspan="5">Location: Bhagwanpur Site (Govt. Inter College)</td></tr>
<tr><td colspan="5">Depth of water table: 2.5 m</td></tr>
<tr><td colspan="5">Bore Hole depth: 8 m</td></tr>
<tr><th>Depth(m)</th><th>Soil Type</th><th>N-value</th><th>Fine content</th><th>Specific Gravity</th></tr>
<tr><td>0.75</td><td>SP</td><td rowspan="7">
</td><td rowspan="7">2.2-15%</td><td>2.65</td></tr>
<tr><td>1.50</td><td>SP</td><td>2.64</td></tr>
<tr><td>2.25</td><td>SP</td><td>2.65</td></tr>
<tr><td>3.5</td><td>SP</td><td>2.63</td></tr>
<tr><td>4.5</td><td>CL</td><td>2.67</td></tr>
<tr><td>6.0</td><td>CL</td><td>2.68</td></tr>
<tr><td>8.0</td><td>SP</td><td>2.64</td></tr>
</table>

The Bahadrabad site is situated on NH 58 which is about 18 km from Roorkee. The SPT was conducted in the ground inside Arya Inter College campus area. The Arya Inter College is situated 100 m from NH 58. The bore hole depth was 9 m at that site. The water table was found at 6 m from the ground surface

<table>
<tr><td colspan="5">Bore Hole: 3</td></tr>
<tr><td colspan="5">Location: Bahdrabad Site (Arya Inter College)</td></tr>
<tr><td colspan="5">Depth of water table: 6 m</td></tr>
<tr><td colspan="5">Bore Hole depth: 9 m</td></tr>
<tr><td>Depth(m)</td><td>Soil Type</td><td>N-value</td><td>Fine content</td><td>Specific Gravity</td></tr>
<tr><td>0.75</td><td>SP</td><td rowspan="8">
</td><td rowspan="8">18.8-32.6%</td><td>2.65</td></tr>
<tr><td>1.50</td><td>SP</td><td>2.64</td></tr>
<tr><td>2.25</td><td>SP</td><td>2.65</td></tr>
<tr><td>3.00</td><td>SP</td><td>2.63</td></tr>
<tr><td>4.50</td><td>CL</td><td>2.67</td></tr>
<tr><td>6.50</td><td>SP</td><td>2.68</td></tr>
<tr><td>7.50</td><td>SP</td><td>2.64</td></tr>
<tr><td>9.00</td><td>CL</td><td>2.65</td></tr>
</table>

The Haridwar site is situated on NH 58 which is about 32 km from Roorkee. The SPT was conducted in the ground inside Pannalal Bhalla Municipal College campus area. The bore hole depth was 6 m at that site. The water table was below 6 m from the ground surface

<table>
<tr><td colspan="5">Bore Hole: 4</td></tr>
<tr><td colspan="5">Location: Haridwar Site (Pannalal bhalla Municipal College)</td></tr>
<tr><td colspan="5">Depth of water table: below 6 m</td></tr>
<tr><td colspan="5">Bore Hole depth: 6 m</td></tr>
<tr><td>Depth(m)</td><td>Soil Type</td><td>N-value</td><td>Fine content</td><td>Specific Gravity</td></tr>
<tr><td>0.75</td><td>SP</td><td rowspan="5">
</td><td rowspan="5">20.8-32.6%</td><td>2.66</td></tr>
<tr><td>1.50</td><td>SP</td><td>2.70</td></tr>
<tr><td>3.00</td><td>SP</td><td>2.68</td></tr>
<tr><td>4.50</td><td>SP</td><td>2.67</td></tr>
<tr><td>6.00</td><td>SP</td><td>2.68</td></tr>
</table>

4.3 Index Properties and Grain Size Distribution

The samples were collected from 4 sites at different depths using SPT (Standard Penetration Test) according to IS 2131:1981. Then several laboratory routine test were carried out on the collected samples to evaluate the index properties of the soil i.e. grain size distributions (IS: 2720 Part4-1983); specific gravity (IS: 2720 Part 3-1980) and relative density (IS: 2720 Part 14-1986). These tests have been conducted and reported by Kirar (2016) for all four sites and reproduced below.

4.3.1 Solani Riverbed Site

At this site, SPT was conducted and 4 samples were collected at the 0.75 m interval and last sample is taken at the 3.5 m. Than several tests were done on these samples to know the basic properties of the soil. Grain size distribution curve are given for different depths by sieve analysis in Fig. 4.2. The other index properties are given for sample collected at different depths in Table 4.2.

Table 4.2 Index Properties of Solani Riverbed Site (After Kirar 2016)

Depth (m)	**C_u**	**C_c**	**Soil Type**	**e_{max}**	**e_{min}**	**γ_d (KN/m^3)**	**e**	**RD (%)**	**Specific Gravity**	**N value**
0.75	2.3	1.1	SP	0.87	0.26	15.85	0.66	33.64	2.64	7
1.5	2.2	0.9	SP	0.88	0.22	15.60	0.69	28.00	2.65	4
2.25	2.2	1.1	SP	0.85	0.39	16.29	0.61	51.87	2.63	12
3.5	2.1	1.0	SP	1.01	0.27	16.63	0.60	55.06	2.66	12

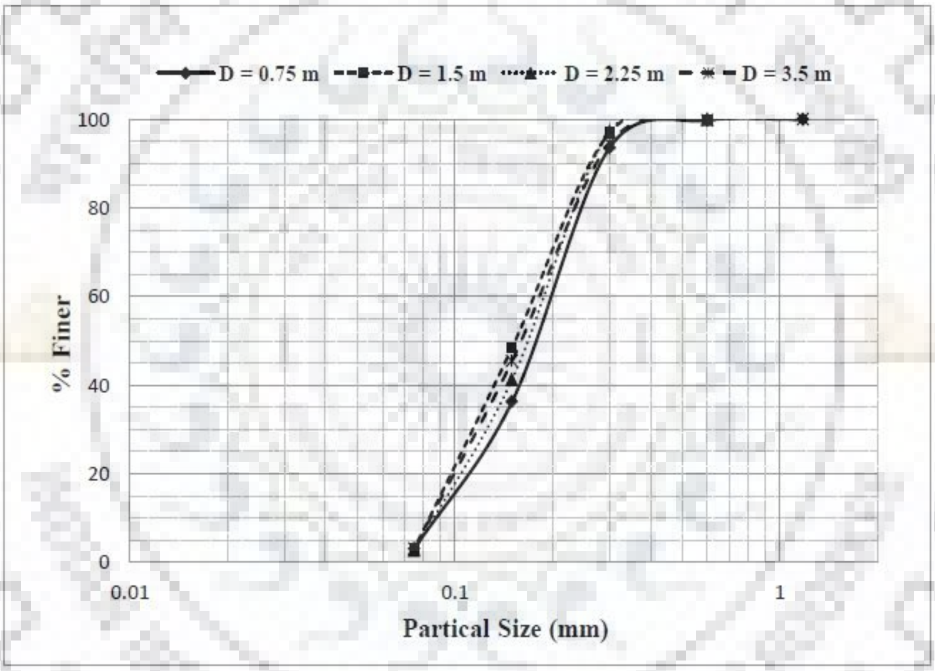


Figure 4.2 Grain size distribution for Solani site (After Kirar 2016)

4.3.2 Bhagwanpur Site

At this site, SPT was conducted and 7 samples were collected at the different interval and last was taken at the 8 m. Than several tests were done on these samples to know the basic properties of the soil. Grain size distribution curve are given for different depths by sieve analysis in Fig. 4.3. The other index properties are given for sample collected at different depths. Sample collected from the depth of 4.5 m and 6 m were clay samples. Hence classification of these clay samples is done on the the basis of plasticity index. The classification of properties of both sand and clay sample described in Table 4.3 and Table 4.4 respectively.

Table 4.3 Index Properties for Sand of Bhagwanpur Site (After Kirar 2016)

Depth (m)	C_u	C_c	Soil Type	e_{max}	e_{min}	γ_d (KN/m^3)	e	RD (%)	Specific Gravity	N value
0.75	2.43	1.11	SP	0.81	0.26	15.80	0.67	25.52	2.65	2
1.5	2.19	1.15	SP	0.85	0.16	16.63	0.58	38.94	2.64	6
2.25	2.0	1.19	SP	0.90	0.31	16.10	0.64	43.81	2.65	8
3.5	1.84	1.06	SP	0.93	0.21	17.33	0.51	57.31	2.63	9
8.0	2.44	1.19	SP	0.75	0.30	17.76	0.48	60.63	2.64	10

Table 4.4 Index Properties for Clay of Bhagwanpur Site (After Kirar 2016)

Depth (m)	LL %	PL %	PI %	Soil Type	Specific Gravity	γ_d (KN/m^3)	e	N value
4.5	74	33	41	CL	2.67	14.57	0.83	8
6.0	44	23	21	CL	2.68	14.73	0.81	5

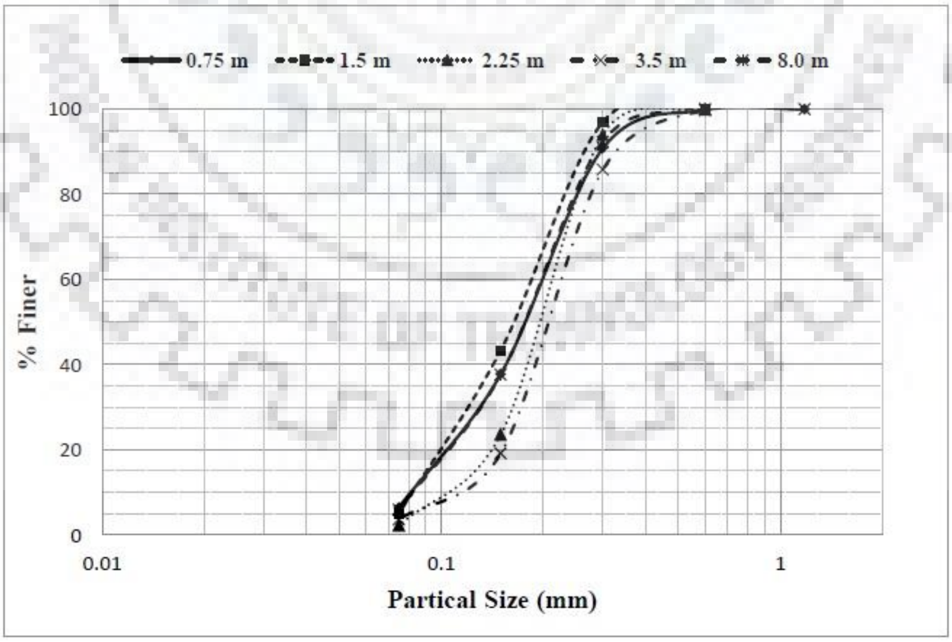


Figure 4.3 Grain size distribution for Bhagwanpur site (After Kirar 2016)

4.3.3 Bahadrabad Site

At this site, SPT was conducted and 8 samples were collected at the different interval and last was taken at the 9 m. Than several tests were done on these samples to know the basic properties of the soil. Grain size distribution curve are given for different depths by sieve analysis in Fig. 4.4. The other index properties are given for sample collected at different depths. Sample collected from the depth of 4.5 m and 9 m were clay samples. Hence classification of these clay samples is done on the basis of plasticity index. The classification of properties of both sand and clay sample described in Table 4.5 and Table 4.6 respectively.

Table 4.5 Index Properties for Sand Bahadrabad Site (After Kirar 2016)

Depth (m)	Soil Type	e_{max}	e_{min}	γ_d (KN/m^3)	e	RD (%)	Specific Gravity	N value
0.75	SP	0.82	0.22	16.57	0.61	36	2.66	8
1.5	SP	0.85	0.28	16.71	0.59	44	2.67	9
2.25	SP	0.92	0.28	16.85	0.58	52	2.67	10
3.00	SP	0.96	0.33	17.15	0.56	63	2.68	17
6.50	SP	1.12	0.12	16.37	0.61	51	2.64	8
7.50	SP	0.85	0.39	16.53	0.60	54	2.65	8

Table 4.6 Index Properties for Clay Bahadrabad Site (After Kirar 2016)

Depth (m)	LL %	PL %	PI %	Soil Type	Specific Gravity	γ_d (KN/m^3)	e	N value
4.5	53	23	30	CL	2.69	17.08	0.58	11
9.0	55	33	22	CL	2.70	15.80	0.70	8

4.3.4 Haridwar Site

At this site, SPT was conducted and 5 samples were collected at the different interval and last sample is taken at the 6 m. Than several tests were done on these samples to know the basic properties of the soil. Grain size distribution curve are given for different depths by sieve analysis in Fig. 4.5. The other index properties are given for sample collected at different depths in Table 4.7

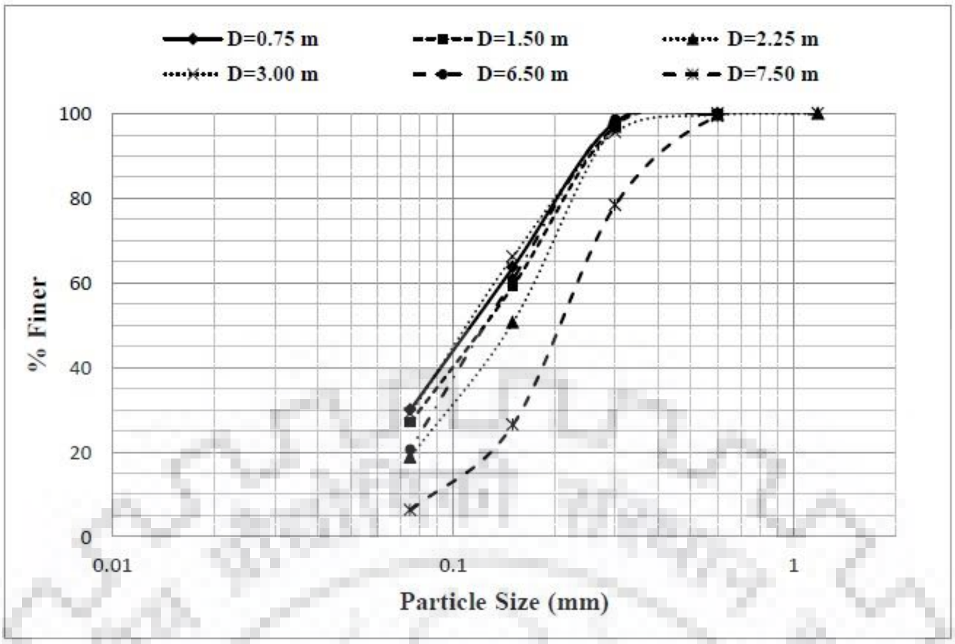


Figure 4.4 Grain size distribution for Bahadrabad site (After Kirar 2016)

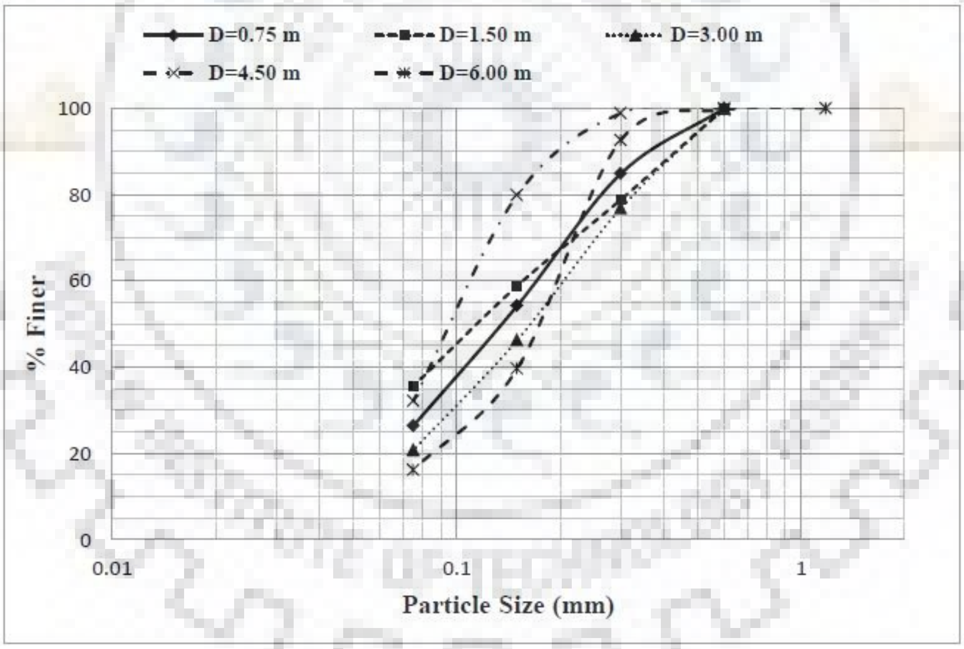


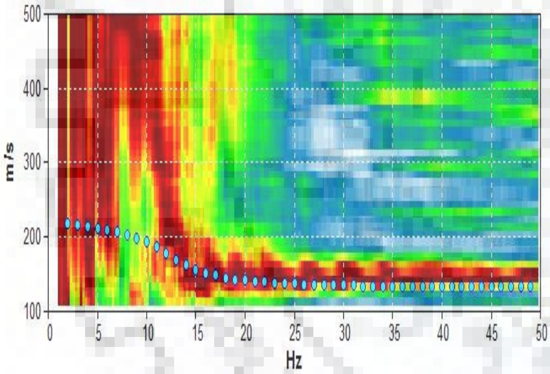
Figure 4.5 Grain size distribution for Haridwar site (After Kirar 2016)

Table 4.7 Index properties of Haridwar site (After Kirar 2016)

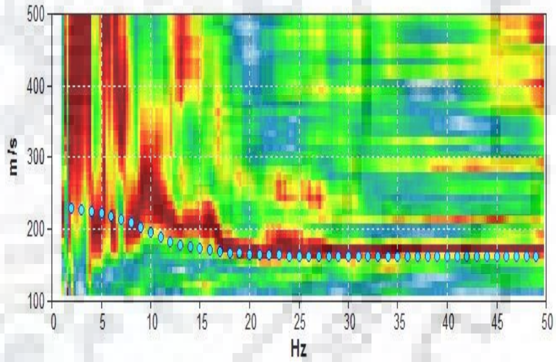
Depth (m)	**Soil Type**	e_{max}	e_{min}	γ_d **(KN/m³)**	**e**	**RD (%)**	**Specific Gravity**	**N value**
0.75	SP	0.93	0.25	15.94	0.67	38	2.66	7
1.5	SP	0.96	0.27	16.45	0.64	46	2.70	8
3.0	SP	1.09	0.21	17.18	0.56	60	2.68	15
4.50	SP	0.99	0.25	16.44	0.62	50	2.67	10
6.0	SP	1.01	0.28	16.68	0.61	55	2.68	12

4.4 MASW Test Results

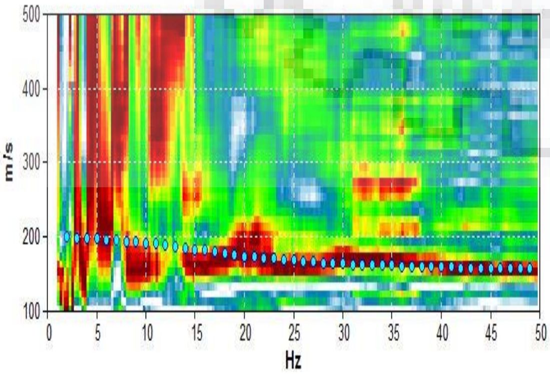
MASW test has been conducted for four sites (Solani riverbed, Bahadrabad, Bhagwanpur and Haridwar) in Roorkee-Haridwar region. The raw field data is aquatinted through soil-spy and has been converted into dispersion curve by Grilla Software. The dispersion curve obtained from the MASW tests has been presented in Fig. 4.6.



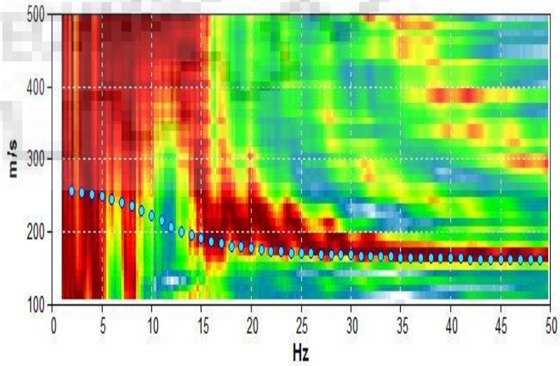
Solani riverbed site



Bhagwanpur site



Bahadrabad site



Haridwar site

Figure 4.6 Dispersion curves for all four sites

The spacing between geophones has been taken 2m for Solani riverbed, Bahadrabad and Haridwar sites due to unavailability of space. The 4m spacing between geophones has been taken for the Bhagwanpur site. High scattering has been observed at the lower frequency i.e. below 15Hz as shown in Fig. 4.6. The variation of shear wave velocity V_s with depth for all four sites has been combined and shown in Fig. 4.7. The shear wave velocity of Haridwar site has been found higher than the other site at most of the depths because of the presence of dense soil deposit and water table at a greater depth. The shear velocity for Solani riverbed site found out to be on lower side because of riverbank material may be loosely packed. There has been decrement in shear velocity on Bhagwanpur site for the depth range 2 to 3m, this may be due to the presence of water table. At Bahadrabad site, general trend has been found out i.e. shear velocity increases with the depth.

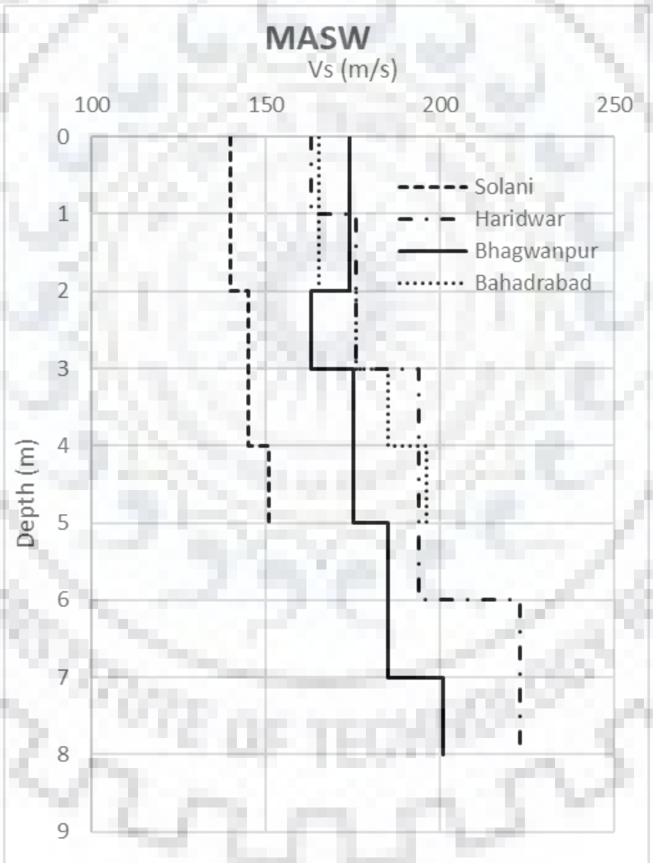


Figure 4.7 Variations of shear wave velocity (V_s) with depth for all sites using MASW

4.5 Bender Element Test Results

Kirar (2016) reported the values of G_{max} with depth for all four sites based on bender element tests. Using these data shear wave velocity V_s is computed and shown in Fig. 4.8. The all sites shown general trend i.e. shear velocity increases with the depth for the sandy samples because generally shear modulus increases with the depth. The clay sample of Bahadrabad and Bhagwanpur region has been excluded because sample preparation of clay sample for Bender Element test is a rigorous exercise. The maximum shear velocity on the solani riverbed site is about 150m/sec. The shear wave velocity of Solani riverbed site has been found out lower than all other site which indicates loose soil deposits.

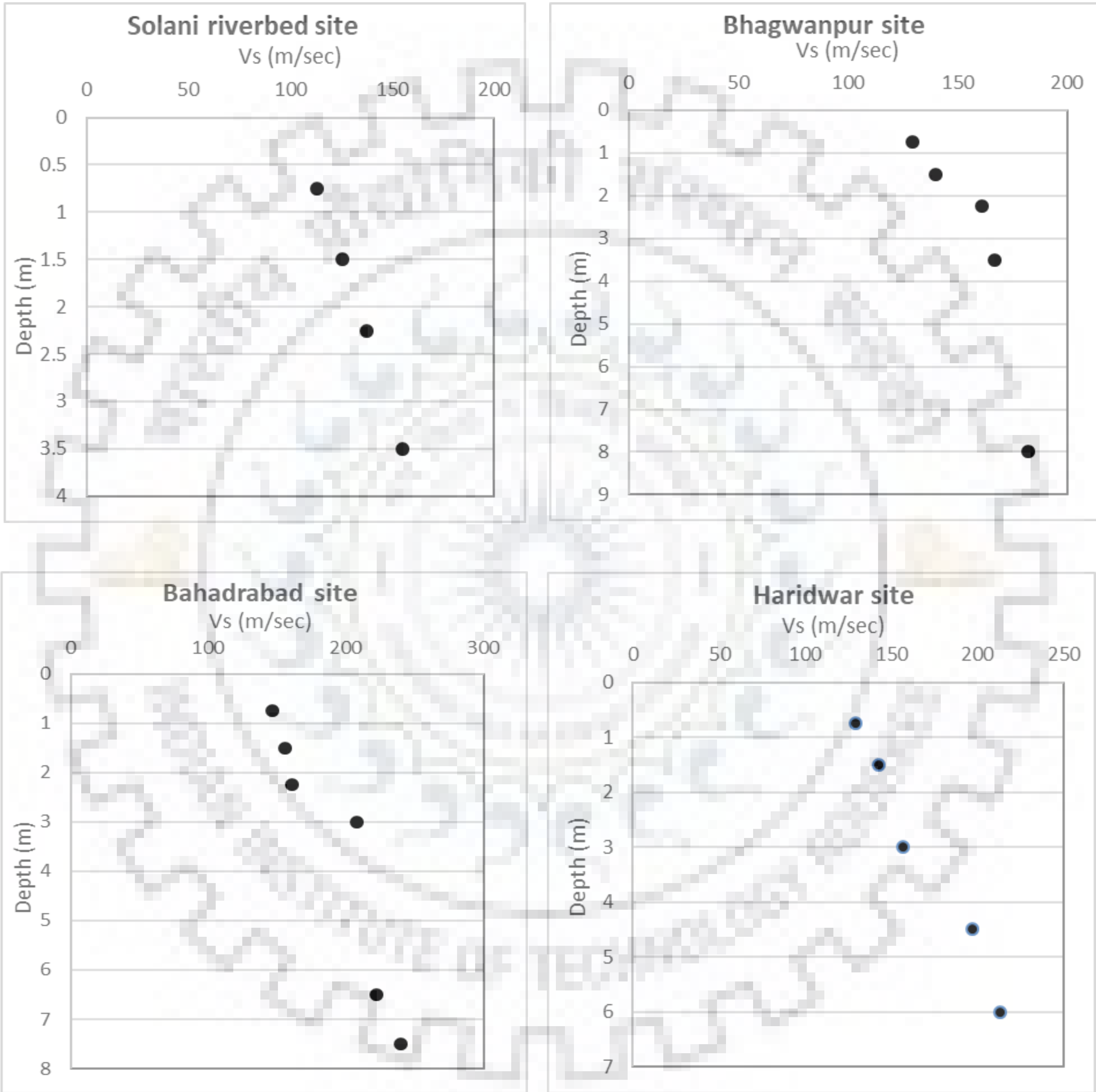


Figure 4.8 Variations of shear wave velocity (V_s) with depth for all sites using bender element test

4.6 SPT Test Results

Based on the SPT N-value reported in section 4.2 and using following empirical relation, shear wave velocity V_s is computed and shown in Fig 4.9.

$$V_s = 61N^{0.5} \tag{4.1}$$

The above equation to find out the shear velocity is given by Seed and Idriss (1981). The Solani riverbed site results have shown decrement in shear velocity at 1.5m depth because of water table at the depth of 2m. There has been a decrement in shear wave velocity for three sites (Bahadrabad, Bhagwanpur and Haridwar) because of clay present in that soil column. The general trend has been noted in the shear velocity i.e. it is generally increases with depth because of shear modulus increases with depth. The shear velocity of Haridwar site has been found higher than other sites because there was a presence of boulder in the soil.

4.7 Comparison of SPT, Bender Element and MASW Test Result

The comparison of shear velocity determined by all three methods has been shown in Fig. 4.10. It has been found out that the shear velocity from Bender Element is on lower side as compares to MASW and SPT. The results from all tests conducted on Haridwar and Bhagwanpur site have been found out very close to each other at some depths. The other two sites have some fluctuations in the shear velocity at most of the depths. The major deflections in the reading has been found out in the SPT results compared to the others. For the Haridwar and Bhagwanpur sites, at the depth of 4.5 and 6m the shear velocity V_s has been almost equal from all different tests. For Bahadrabad site, comparison of shear velocity is difficult after 5m because the disturbances at that site which cause difficulties in data extraction from MASW.

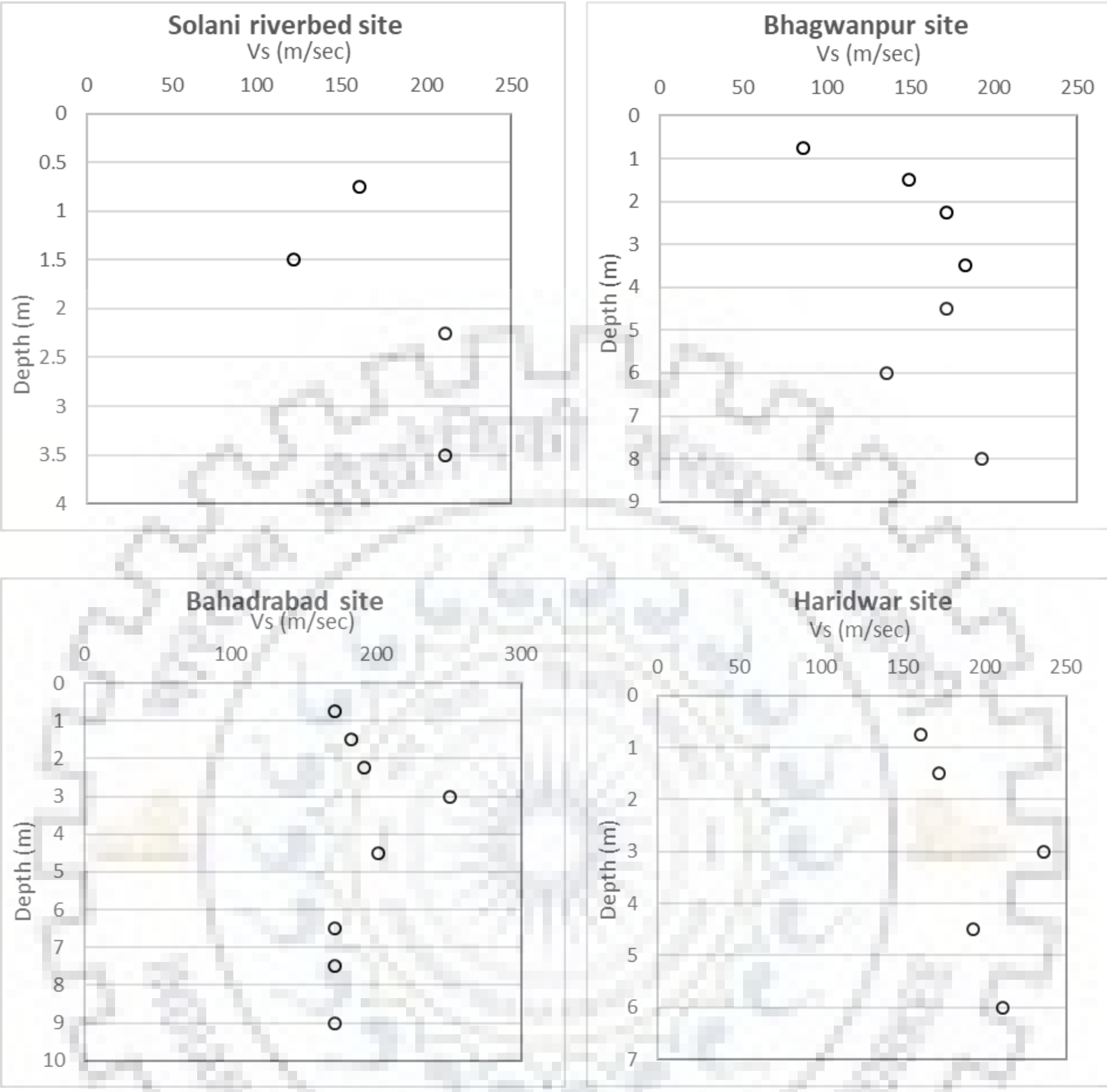


Figure 4.9 Variations of shear wave velocity (V_s) with depth for all sites using SPT-N value

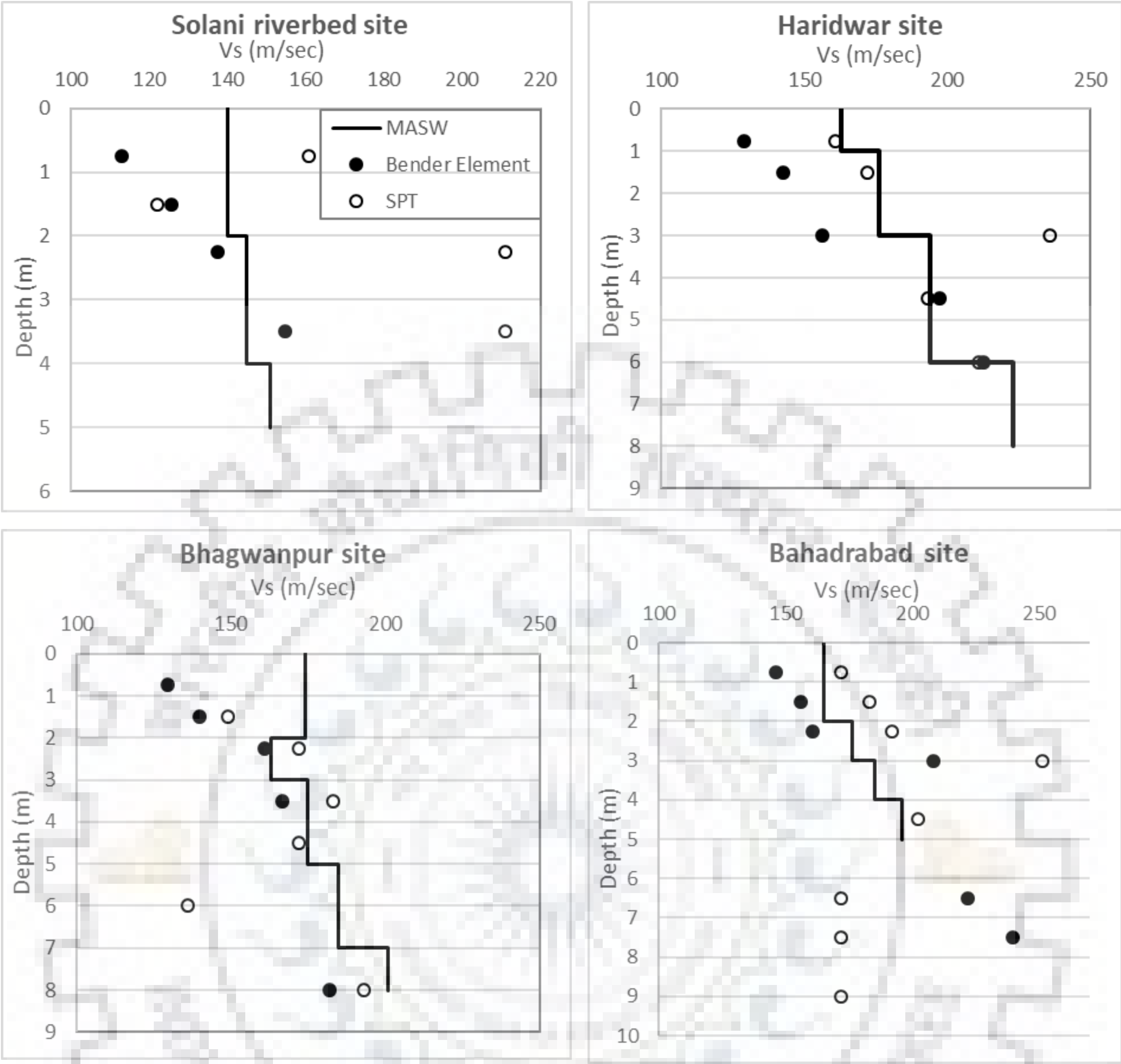


Figure 4.10 Comparison of shear wave velocity (V_s) with depth for all sites

It is important to know the actual numerical difference between shear velocity obtained from Bender Element and MASW. The Table 4.8 shows the percentage by which the MASW shear velocity is higher than the shear velocity obtained from Bender Element for all four sites of the Roorkee-Haridwar region. Basically, the shear velocity obtained from MASW has been on higher side for the upper portion of the soil column. Shear velocity obtained from Bender Element is higher than MASW at greater depth in soil column i.e. more than 3m for all the sites except Bhagwanpur site.

Table 4.8 Percentage increase MASW V_s from Bender Element V_s for all site

Site	Depth	V_{s1}(Bender Element	V_{s2} (MASW)	$\frac{V_{s2} - V_{s1}}{V_{s1}}$ (in %)
Solani Riverbed	0.75	113	140	24
	1.5	126	140	11
	2.25	137	145	6
	3.5	155	145	-7
Haridwar	0.75	129	163	26
	1.5	142	176	24
	3	157	176	12
	4.5	197	194	-1.5
	6	213	194	-9
Bhagwanpur	0.75	130	174	34
	1.5	140	174	24
	2.25	161	163	1.2
	3.5	167	175	4.7
	8	182	201	10
Bahadrabad	0.75	146	165	13
	1.5	156	165	6
	2.25	161	176	9
	3	208	185	-11

4.8 Correlation between V_s from laboratory and field tests

The soil deposits always have significant effect on characteristics of an earthquake motion at a site. Simplified site classification or specific ground response analysis can be used to estimate ground motion characteristics. But for all these methods, shear velocity is an important parameter for the study. In this study a correlation has been made between V_s (shear velocity) found out by Multichannel Analysis of Surface Wave (MASW) and Bender Element tests for soils of Roorkee region.

There are several studies carried out for the different region of India and worldwide also in which they show correlation between V_s and N values. But there are very few studies in which there is comparison between field and laboratory test of any parameter regarding geotechnical studies. If there is difficulty in doing laboratory tests this correlation helps us to find out the shear velocity

A regression analysis has been done in the MS Excel on the data collected from all four sites irrespective of soil condition. This regression analysis helps to determine the best curve fit plot line between shear velocity from MASW and Bender Element.

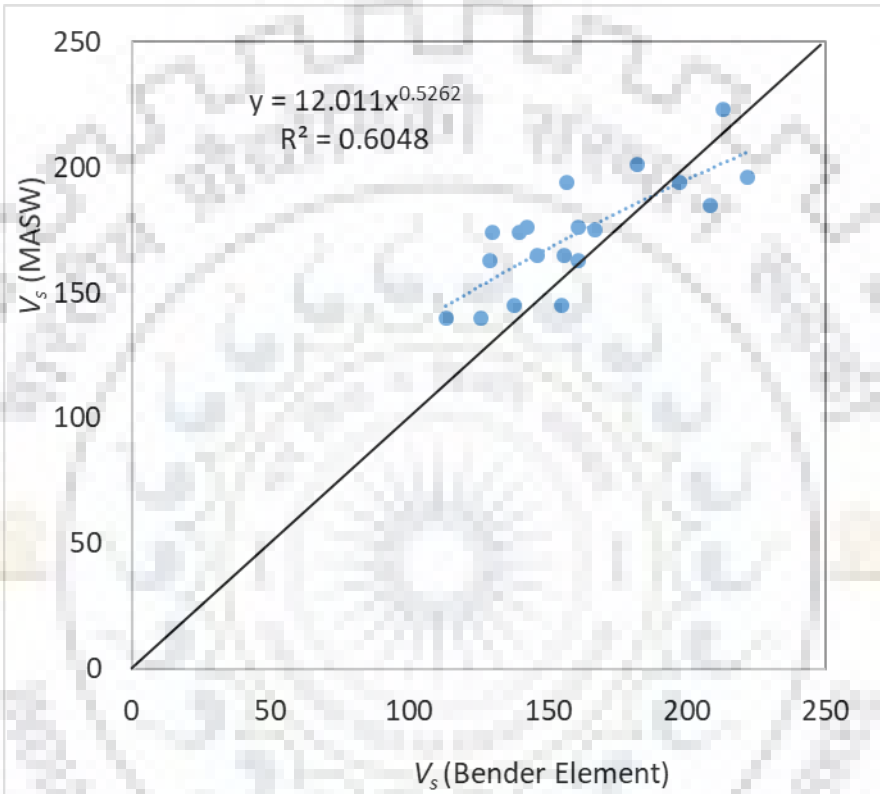


Figure 4.11 Correlation between field V_s (MASW) and laboratory V_s (Bender Element)

The equation is setup between V_s of Bender Element and MASW shows in the Fig 4.11. The R^2 achieves is .6048 in the regression analysis. The equation found out in that study is

$$(V_s)_{MASW} = 12.011(V_s)_{BE}^{0.5262} \tag{4.2}$$

$R^2 = 0.6048$, $100 < V_s < 250$

Chapter-5

SUMMARY AND CONCLUSIONS

5.1 Summary and Conclusions

From the present experimental study at four sites i.e. (Solani riverbed, Bahadrabad, Bhagwanpur and Haridwar) within Roorkee-Haridwar region, the following conclusions can be drawn:

1. The present test results of MASW have been compared with past available test results of V_s using SPT and bender element test which shows a good agreement at some depths. The V_s using MASW tests falls in between those obtained from bender element and SPT.
2. The high scattering is observed below 15 Hz frequency in MASW dispersion curve.
3. From the field measurement of shear wave velocity using MASW test, it has been observed that in general the V_s increased with depth as observed for all sites.
4. A correlation has been developed between laboratory and field shear wave velocity V_s collecting data from all four sites. The shear wave velocity from bender element results is quite lower as compared to MASW test results, especially at shallow depth i.e. 3m. From the collected data it can be noted that distribution of MASW results is dominated then the Bender Element results.

5.2 Future Scope of Work

1. Number of sites can be increased for the better correlation and for increasing the range of the V_s in the correlation the sites of wide range of properties can be taken.
2. Numerical model study based on dispersion curve can also be consider.

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