In-situ dynamic properties and V_s30 for soil using multi-channel analysis of surface waves

Abstract: In present research, V_s30 and dynamic properties of soil for ten identified sites in the campus of the Rajiv Gandhi Technological University located in Bhopal (India) are evaluated using MASW method. Shear wave velocity (V_s) profile using three steps procedure consisting of obtaining multichannel data record on field, dispersion curve analysis and inversion is generated. The properties of soil such as density, shear modulus and poison's ratio are calculated using MASW. The poisson's ratio, soil density and the shear modulus are observed to vary in the ranges of 0.41 to 0.27, 1.80 to 2.11 g/cc and 46 to 409 MPa respectively along depth of soil. The shear wave velocity across depth is varying between 160 to 407 m/s indicating change in soil type from mostly soft clay soil, stiff soil to a very dense soil and soft rock.

Keywords: Multichannel Analysis of Surface Waves (MASW), Seismic exploration, Dynamic soil properties, Site-response, Site-characterization

1. Introduction

The Multichannel Analysis of Surface Waves (MASW) method is increasingly used for geotechnical investigations, soil profiling, measuring dynamic properties of soil and related site response studies. This non-destructive technique is time-efficient and, thus, popular for field assessment, ground profiling applications such as mapping of the rock layer and evaluate pavement thickness, elastic modulus of ground and materials under the pavement.

The measured dynamic property such as maximum shear modulus (G_{max}) are used for design of structures subjected to cyclic loading. Shear wave velocity (V_s30) has a direct correlation with the stiffness of soil. It is one of the most significant engineering parameters pertinent for assessment of soil liquefaction [1].

The MASW method involves field survey with simple field logistics such as geo-phones and single impact source (e.g. sledgehammer). The method is based on the principle that the shear waves respond most effectively to various types of inter layer anomalies during sub-surfaces [2].

The components of MASW used in present investigations are depicted in Fig 1[3]. MASW unit consists of 24 channels Geode seismograph, 24 geo-phones (4.50 Hz capacity each). The captured Rayleigh wave is analyzed using the 'winMASW7.2 Academy' software package.

2. Background

MASW, based on variety of instrumentations and field methods, has been used for wide applications of sub-surface soil assessment and profiling globally. Significant research in this area is discussed below in brief:

A study on a site located in a basement complex in Zaria (Nigeria) was carried out. The test was carried out with a receiver array of 1.0 m distance and a maximum offset distance of 10 m from the first receiver. The stacking was done five times during data acquisition. The seismograph observations were recorded after a full shot and the source was advanced by 1.0 m. The first receiver was taken ahead of other receivers and placed 1.0 m beyond the last receiver. Sledge-Hammer was used as a 'source'. The V_s models showed increase in velocity with depth. This research also revealed that northern part is experiencing more weathering than southern part, which is characterized by relatively harder material with more resistance to weathering [4].

A 'passive' roadside MASW survey in cricket ground with adjacent four-lane road in IIT, Guwahati (India) was performed. The receiver was located in two different sites with an inter receiver spacing of 2m with a total length of 46m for spread. The first site was 5m away from the road, and the second site was 20m away from the road. The time of acquisition is kept sufficient so that at least one vehicle passed during the acquisition time. The acquisition time was kept 10.80 seconds for 'passive' survey. Two sources used for observations, the first source was an inter-line source, and the second one was the outer-line source. The dispersion images obtained from the inter-line source were reasonable in comparison to the one received by the outer-line source. It was inferred that number of sources enhanced the bandwidth of the frequency spectrum in the dispersion image for the 5m case and increasing distance by 20 m reduced the resolution of the dispersion image [5].

Seismic Refraction test was performed at seven locations within NIT Silchar, India campus. The S-wave velocity obtained from the Seismic Refraction Test was used for characterization and stratification of soil. Limited number of boreholes were dug at selected locations and SPT tests were carried out. Samples were also collected from different layers for obtaining the soil properties. The correlation between standard penetration N value and S-wave velocity obtained from the Seismic Refraction test was established and found to be non-linear [6].

Results obtained using MASW and cross-hole test were compared. The tests were conducted with different minimum offset by changing seismic sources. Data processing was performed using the GEOPSY software. The results showed that adopted minimum offset significantly influenced the quality of the image obtained, whereas variation of the seismic source had showed a little influence on final results. The results obtained with MASW method were generally found closely matching with results of the cross-hole test. Results were also found to be compatible with the SPT test data [1]. A field survey was carried out on two straight stretches of easy and long receiver array, inside campus and surrounding areas of IIT Guwahati (India). Tests were carried out with different stacking range from 1 to 10 with inter receiver spacing up to 2 m. The effect on dispersion images for 'passive' MASW was investigated. Ten field records were measured for different acquisition time ranging from 0.7 sec to 218 sec. It was concluded that 5 to 10 number of stacking samples provides better resolution [7].

Multichannel analysis of surface waves in Delhi region at 118 sites with a predefined grid of 2.0 KM to 3.0 KM was proposed. The dynamic behavior of soil was determined using shear wave velocity and its essential parameters were studied. This investigation was done using 48 seismograph channels with 4.5Hz. Data was analyzed with relevant software and 2D profile of shear wave velocity model for every 5.0m depth was obtained. It was observed that value of shear wave velocity ranged from 400 to 480m/s in the rocky sites. Velocity in the range of 120 to 250m/s were observed in the region corresponding to soft soil and 250 to 370m/s in the western side of the area indicated the presence of soft rock [8].

Dynamic properties of soil were determined at many locations in Bangalore, Hyderabad, and Delhi. Profiling survey was carried out, and ground anomalies were also measured in different locations of Bangalore. Results of investigations were used for selecting filling materials for the construction sites, suitable equipment's and methods of construction. The measured dynamic properties were used for structural design for cycle/earthquake loading conditions. Advantages and suitability of MASW system and related engineering applications were reiterated in this study [9].

Shear modulus using Multichannel Analysis of Surface Waves (MASW) method for two soft clay sites in Ireland were measured. Profiles generated using MASW method were comparable with values derived empirically from Cone penetration test probe equipped with a pore-water pressure sensor (CPTU) data and also with results of laboratory testing. A synthetic earth model generated using a Discrete Particle Scheme (DPS) was also used to evaluate the software. The results by the MASW method were compatible with both the conventional seismic methods and the synthetic model [10].

3. Present research

The primary objective of present study is to map the soil and rock layers at sites in the campus of Rajiv Gandhi Technological University located at Bhopal (India) and finding dynamic properties of site material. Soil profiling is performed at different locations for measurement of dynamic properties like density of soil, shear modulus, poisson's ratio using the 'active' source method of MASW (Multi-Channel Analysis of Surface Waves) Test. The value of V_s30 for different locations is found for the 'best and mean' model using

'WinMASW 7.2 Academy' software package. The shear wave velocity (V_s30) is measured for different sites on the campus, and the soil classification is done on the basis of shear wave velocities observed at different depths. Experimental and proxy methods can be used to determine the Vs30 values. Experimental methods are time-consuming and demand significant effort in terms of mobility and experimentation; in comparison, proxy methods are simpler to perform. Slope-based proxy methods are increasingly acknowledged and employed worldwide, particularly in places where experiments are impractical. Also, the United States Geological Survey (USGS) maintains a global Vs30 mosaic based on high-resolution ASTER satellite slope data for many parts of the world. Additionally, this study makes use of it and compares the experimental results to the standard estimated Vs30 values acquired from the USGS database (https://earthquake.usgs.gov/data/vs30/).

4. Site location and methodology

4.1. Site Location

The Rajiv Gandhi Proudyogiki Vishwavidyalaya (RGPV), Bhopal campus is selected for the MASW Survey due to its significance and large availability of open space needed for survey. This campus is situated in Gandhi Nagar, Bhopal. The ten sites are chosen so as to cover the whole campus and different topographies. The map and geographical coordinates of the sites are shown in Fig 2 [11].

4.2. Methodology

Present Research is performed using twenty-four geophones of 4.5 Hz vertically inserted in the ground. Twelve geophones are connected at each side of seismograph with connecting cable as shown in Fig 3. Geophones are installed on ground surface at a spacing of 2.0 m throughout the length. An 'active' source is formed by striking a hammer of 11.0 kg weight on a 20 cm square aluminum plate. Trigger geophone is inserted near striking plate to record the time of striking. The acquisition of data is made sequentially on all ten different sites chosen on the basis of their coverage and topographical differences. The 'PASI Gea24' exploration seismograph is used for data acquisition on field. Field data thus acquired contains much noise due to activities in surroundings. Hence, noise filtration is done using 'Geogiga geophysical software'. The software used for dispersion Curves are generated through processing in 'WinMASW VERSION 7.2 Academy' software. The V_s30 soil profile is calculated through iterative inversion with dispersion data as input after getting the desired shape of velocity spectrum. V_s velocity versus depth curve, mean model, best model, the value of V_s30 for the mean model, and value of V_s30 for best model are obtained through further processing.

5. Data acquisition

A multiple number of receivers with 24 geophones deployed with uniform spacing along a linear survey line connected to a multi-channel recording device of geophone. Each channel is dedicated for recording vibrations from one receiver. One Multi-Channel record, commonly called a 'Shot gather' consists of a multiple number of time series, called 'traces' from all receivers in an ordered manner. Schematic arrangements on field site are shown in Fig 4 [12].

6. Data processing

The data processing consisted of three distinct steps, namely, data filtration of raw field, data generation of dispersion curve and iterative inversion process for calculating V_s30 soil profile. Data filtering is done for removing the unwanted noise from the raw data in the common file of three stacking. 'Geogiga geophysical software' is used for data filtering. The plot of phase velocity (m/s) versus frequency (Hz) also known as 'Dispersion Curve' are produced by processing the filtered data using the 'Geogiga Front End' software. The dispersion curves for the recorded data are shown in Fig 5. 'WinMASW 7.3 Academy' version software is used for data processing.

The process for finding inversion for V_s is done after getting the desired shape of the velocity spectrum. V_s profile is calculated using a process of iterative inversion with dispersion data as input. Iteration only V_s is updated without changing parameters such as Poisson's ratio, density, and thickness of the model. Output of V_s profile is shown in Fig 6, indicating general soil profile below the ground.

7. Discussion

The MASW field experiments were performed at ten different locations on the university campus, as shown in Table 1. The locations were selected to cover a large campus area without compromising the geological diversity. Data acquisition was performed in active mode using a Pasi GEA24 seismogram with standard acquisition parameters listed in Table 2. All the other accessories utilised to conduct the field experiments are shown in Figure 1. It is worth mentioning that a linear configuration of a 4Hz geophone array was utilised as a significant open area was available on the campus. The acquired data is processed in the standard software (WinMASW, latest version) provided with the seismogram. The various steps involved in transforming the field data into Vs30 values are shown in Figure 3. Figure 5 typically represents the dispersion and inversion curves thus obtained from the data processing using WinMASW software. The software computed Vs30 using two models, i.e., the mean and the best-fit model. Also, Figure 6 depicts the Vs. profile of a particular location on the campus. All the Vs30 values thus obtained from the mean and best-fit models are summarised in Table 7. Figure 7 shows the variation of Vs30 obtained from the mean and best-fit model across the sites. Not much difference is observed for any of the sites. As shown in Table 7, the results indicate a slight difference in the Vs30 values obtained from the mean and the best-fit models, respectively. Although there is a difference, it is not enough to change the soil type as per the NEHRP (National Earthquake Hazard Reduction Program) site classification as given in Table 8. Therefore, either the mean or the best-fit models can classify soil as per NEHRP site classification. Also, the average Vs30 value obtained from the mean and best-fit models was 311.1 m/s and 339.5 m/s, respectively. Hence, both the models classify the campus site as Class D, with Vs30 ranging from 180–360 m/s, as shown in Table 8. Therefore, by and large, the soil of the whole university campus can be treated as "stiff soil." The software also resulted in the other soil properties such as density (Table 4), shear modulus (Table 5), and Poisson's Ratio (Table 6) based on their empirical relations with the Vs30 values. Table 4 indicates an increase in density with depth for all the sites. Also, the average density across the sites is 2.75 g/cc. Similarly, the average shear modulus (Table 5) and the average Poisson's ratio are 158.85 MPa and 0.36, respectively, for the campus. Additionally, the average Vs30 value for test locations collected from the USGS database is 316 m/s. As a result, the MASW-derived Vs30 values are found to be consistent with the usual slope-based Vs30 values acquired from the USGS database.

Overall, the value of shear-wave velocity is found broadly varying from a minimum of 160 m/s to maximum of 407 m/s and it can be concluded that, the soil type is mostly soft clay soil, stiff soil, and very dense soil and soft rock as shown in Table 3. For 1 m depth of soil, shear-wave velocity is found to be less than180 m/s indicating it to be a soft clay soil. For depths between 1.5 meter to 20 m it is found to vary from 190 m/s to 367 m/s indicating stiff soil and for depths between 20 and 30 m, it is measured to be between 360 m/s to 452 m/s implying very dense soil and a soft rock.

8. Conclusions

In the present research, computation of important soil properties and soil profiling is done for ten sites carefully chosen for overall coverage of available topographical differences of site. The dynamic soil properties like soil density, shear modulus and poisson's ratio are measured using the 'active' source method of MASW. The values of V_s30 for the 'best' and 'mean' models are calculated for all the sites using the winMASW7.2 Academy version software. The shear wave velocity (V_s) is also measured, and soil profiling is done based on Vs values.

Following significant conclusions are drawn based on present research:

1. V_s30 and shear wave velocities is measured at ten sites ascertained for experimentation. Based on the field measurements, V_s30 is observed to be varying from 290 m/s to 370 m/s, and the shear wave velocity is found to be varying from 160 m/s to 407 m/s across the depth of 30.0 m from ground level.
2. Both, the mean and the best-fit models classify the campus site as Class D, with Vs30 ranging from

180–360 m/s, and places soil into a stiff soil category. The USGS slope-based proxy method also estimated Vs30 in the similar range thus further substantiating the soil classification.

3. This range of velocities indicates soft clay soil and stiff soil for a depth of 20 m from the ground surface and very dense soil or soft rock for the next 10 m depth.
4. The measured poisson's ratio and soil density are found to be in the range of 0.41 to 0.27 and 1.80 to 2.11 (g/cc) respectively across the depth of soil. The Shear Modulus of soil is found to vary from 46 to 409 (MPa) across 30.0 m depth of the soil.
5. The parameters obtained in this research will be useful for the Micro zonation studies and site characterization of the Bhopal city.

Declarations

Availability of data and material

All data that pertains to this research has already been provided in the article.

Code availability

Not applicable

References

1. Baglari, D., et al. Aspects of dispersion imaging scheme of passive MASW survey for subsurface characterization. in 50th Indian geotechnical conference, Pune. 2015.
2. Park, C.B., R.D. Miller, and J. Xia, Multichannel analysis of surface waves. Geophysics, 1999. **64**(3): p. 800-808.
3. Components of MASW test assembly. Available from: http://civil.iisc.ernet.in/~microzonation/index_files/image102.jpg.
4. Chiemeke, C.C. and O.O. Felix, Structural Characterization of the Zaria Batholith Using Multichannel Analysis of Surface Wave (MASW) Seismic Method. 2018.
5. Baglari, D. and A. Dey. Effects of source characteristics in passive roadside MASW survey. in 52nd Indian geotechnical conference, Guwahati. 2017.
6. Sarkar, S., A. Saha, and A.K. Dey, Soil Characterization and Stratification using Seismic Refraction Test.
7. Eikmeier, C.N., R.L. Prado, and F. Taioli. Tests with the MASW method (Multichannel Analysis of Surface Waves) in the urban area of São Paulo, Brazil. in 14th International Congress of the Brazilian Geophysical Society & EXPOGEF, Rio de Janeiro, Brazil, 3-6 August 2015. 2015. Brazilian Geophysical Society.
8. Satyam, D.N. and K. Rao, Multi channel analysis of surface wave (MASW) testing for dynamic site characterization of Delhi region. 2010.
9. Sitharam, T. and P. Anbazhagan. Measurements of dynamic properties and soil profiling using multichannel analysis of surface waves. in Invited Keynote in 4th Karl Terzaghi Memorial Workshops, October07. 2006.
10. Donohue, S., et al. Use of multichannel analysis of surface waves in determining Gmax for soft clay. in Proceedings 2nd. Int. Conf on Geotechnical Site Characterisation, ISC. 2004.
11. Satellite image of test site location. 2021, CNES/Airbus, Maxar Technologies.
12. Schematic illustration of MASW survey. Available from: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcQLFyIQieN7hndDJANZ7NEF0m4KsBkXX6qlCQ&usqp=CAU.

List of Tables

Table 1 Description of different sites and their co-ordinates throughout the campus

Site	Description of site	Geographical coordinates (Latitude, Longitude)
1	Entrance/Near Temple	23.302,77.360
2	Faculty residence	23.305,77.360
3	Near IT park	23.306,77.361
4	University garden	23.309,77.361
5	UIT ground	23.311,77.361
6	In front of canteen	23.311,77.363
7	In front of SOIT	23.313,77.363
8	In front of SOEE	23.313,77.362
9	In front of stadium	23.313,77.360
10	Near boys hostel	23.315,77.360

Table 2 Various details for data acquisition in GEA24 Seismogram and software

S. No.	Acquisition parameters	Selected options
1.	Acquisition mode	Active
2.	Sampling time	250 micro second
3.	Acquisition time	2000 mili seconds
4.	Pre-trigger time	10 mili seconds
5.	Recording format	SEG 2
6.	Geophones	24
7.	Geophone arrangement	Linear
8.	Spacing	2m
9.	Source	10kg Hammer
10.	Offset	5m
11.	Number of stacking	3

Table 3 Shear wave velocity-V_s (m/sec) at different locations and depths

Depth(m) from ground level	Shear wave velocity-V_s (m/sec)									
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
0.60	167	164	164	162	162	163	163	163	160	160
3.20	242	241	241	236	242	233	227	237	239	242
11.50	263	293	315	313	280	264	253	265	279	311
29.20	375	407	452	398	397	376	401	423	382	406

Table 4 Soil Density (g/cc) at different locations and depths

Depth(m) from ground level	Density of soil (g/cc)									
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
0.60	1.84	1.84	1.80	1.82	1.84	1.83	1.81	1.83	1.80	1.80
3.20	1.90	1.89	1.91	1.93	1.89	1.89	1.86	1.91	1.90	1.92
11.50	1.97	1.97	2.01	1.98	1.93	1.91	1.88	1.90	1.94	1.96
29.20	2.11	1.99	2.00	1.97	1.99	1.97	1.98	1.99	1.98	2.00

Table 5 Shear modulus (MPa) at different locations and depths

Depth(m) from ground level	Shear modulus (MPa)									
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
0.60	51	49	48	48	48	49	48	49	46	46
3.20	111	110	111	108	110	103	96	107	108	113
11.50	134	169	199	194	152	133	121	133	151	190
29.20	275	330	409	312	313	287	318	356	289	330

Table 6 Poisson's Ratio of Soil at different locations and depths

Depth(m) from ground level	Poisson's ratio of soil									
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
0.60	0.41	0.41	0.36	0.39	0.41	0.40	0.38	0.40	0.37	0.36
3.20	0.37	0.35	0.39	0.41	0.35	0.37	0.33	0.39	0.37	0.40
11.50	0.39	0.39	0.41	0.39	0.37	0.36	0.33	0.33	0.37	0.37
29.20	0.27	0.31	0.27	0.27	0.31	0.29	0.28	0.28	0.32	0.33

Table 7 V_s30 (m/sec) for different locations

Location site	V_s30 (m/sec)	
	Mean model	Best model
Site 1	290	290
Site 2	320	360
Site 3	347	365
Site 4	325	360
Site 5	311	334
Site 6	291	319
Site 7	298	356
Site 8	303	309
Site 9	303	332
Site 10	323	370

Table 8 Seismic site classification based on shear wave velocity (V_s) ranges

S. No.	**Site class**	**Type of formation**	**S-velocity (V_s) (m/sec)**
1	A	Hard rock	>1500
2	B	Rock	760-1500
3	C	Very dense soil and soft rock	360-760
4	D	Stiff soil	180-360
5	E	Soft clay soil	<180

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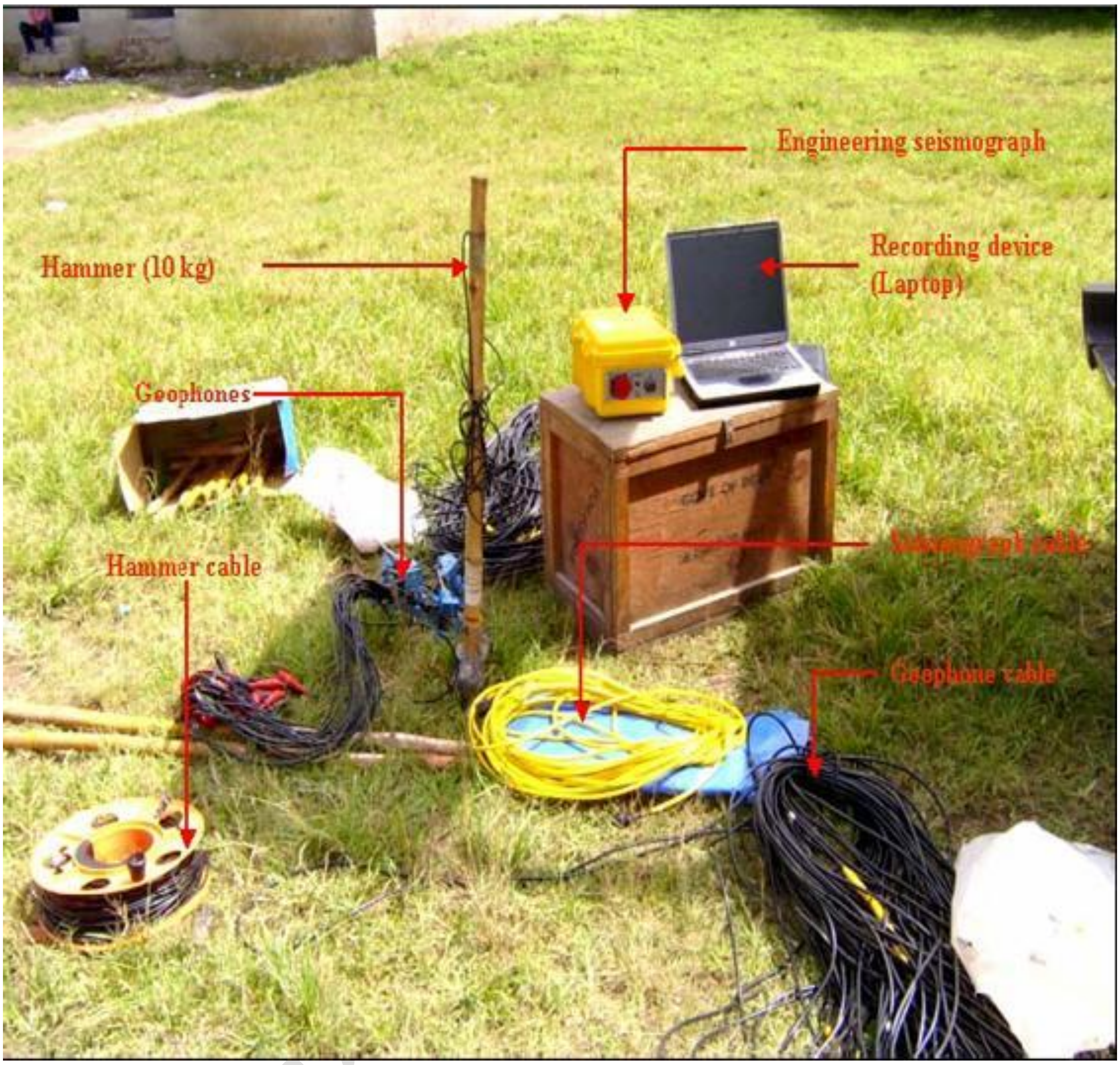

Fig 1 Various components of MASW test assembly

Fig 2 Satellite image of test site location

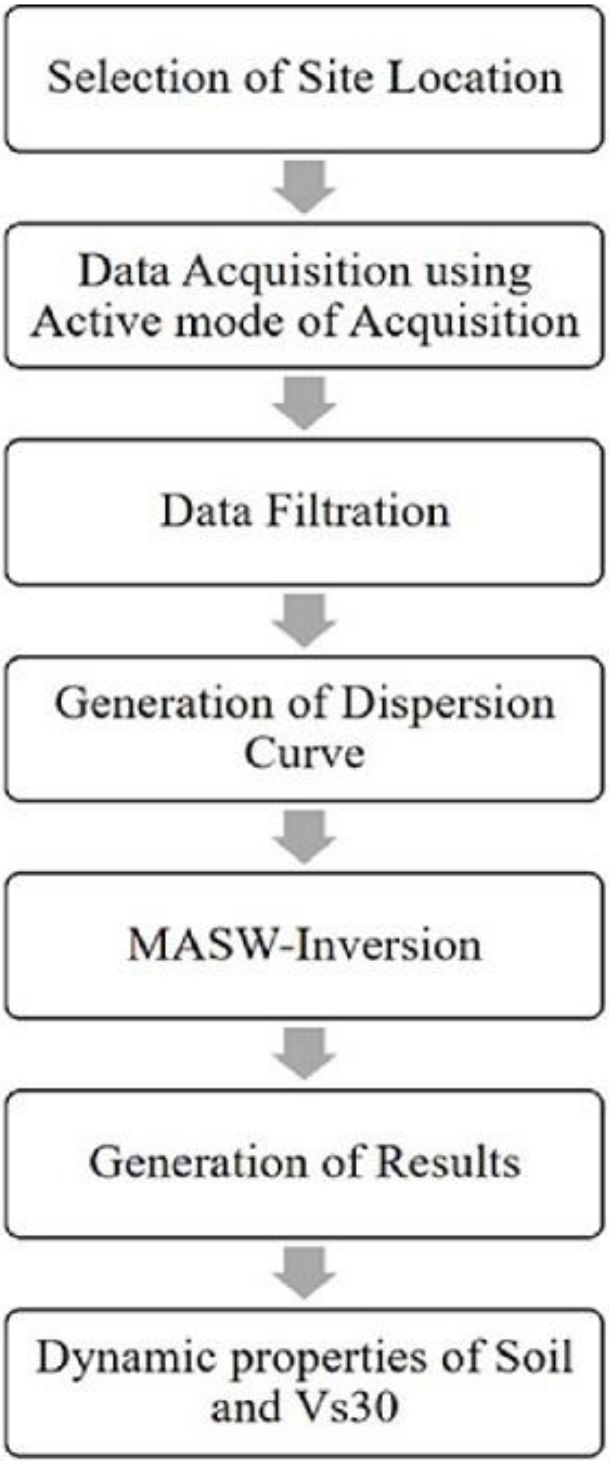

Fig 3 Flow chart depicting the process of MASW test

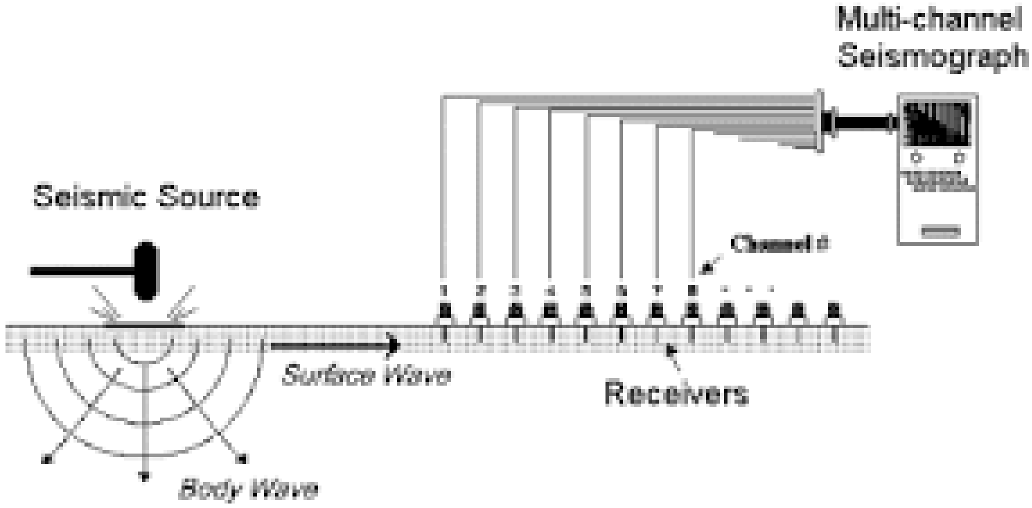

Fig 4 Schematic illustration of MASW survey

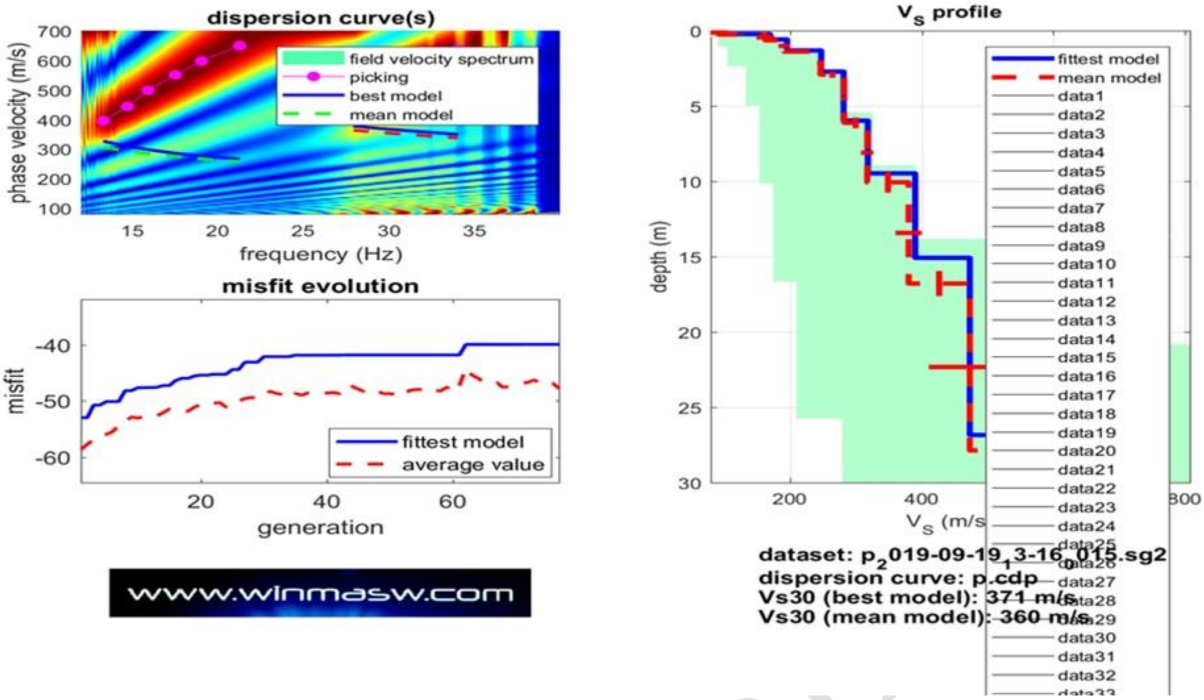

Fig 5 Dispersion curves obtained by processing with WinMASW software

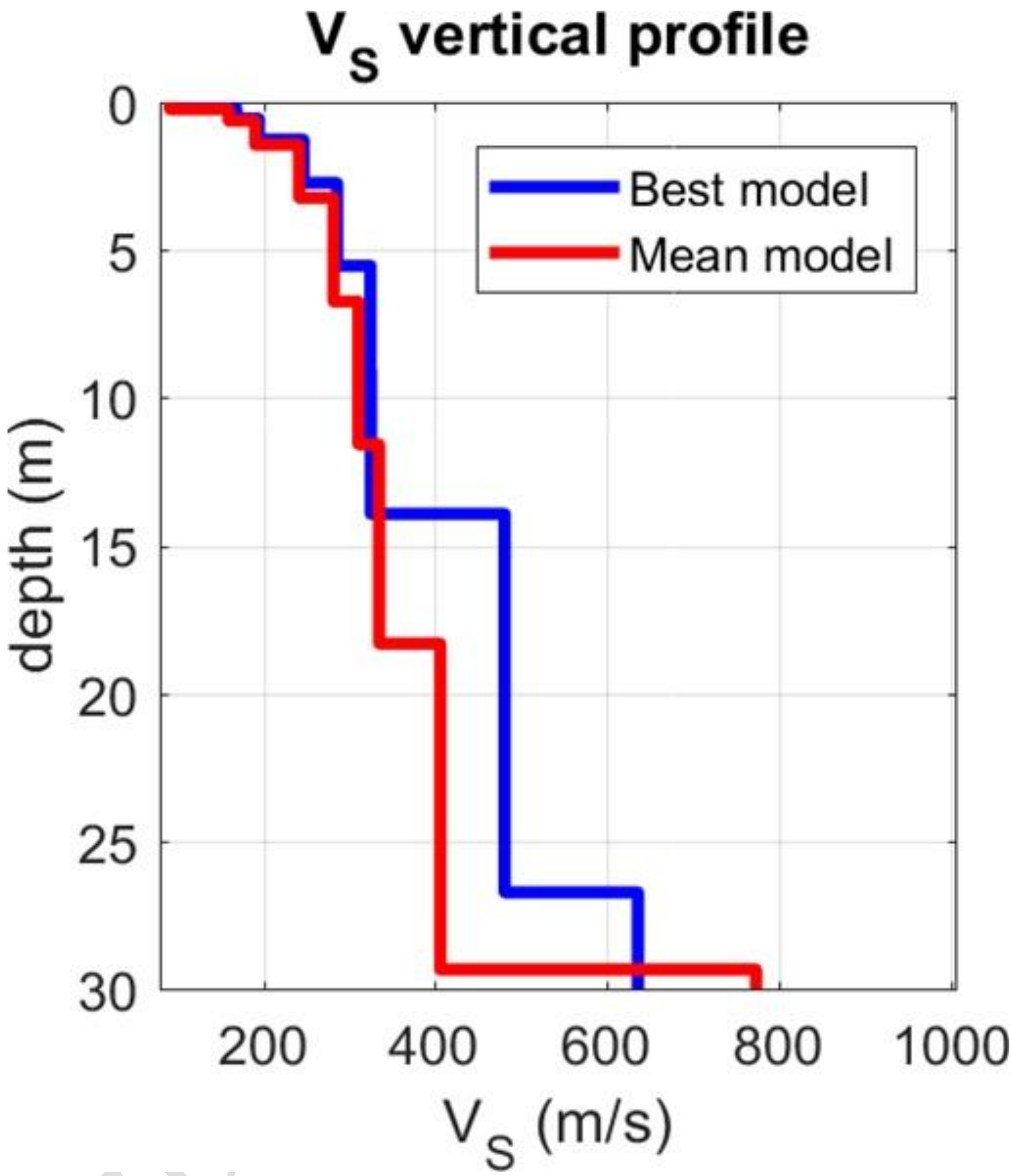

Fig 6 V_s profile obtained after processing of MASW field data

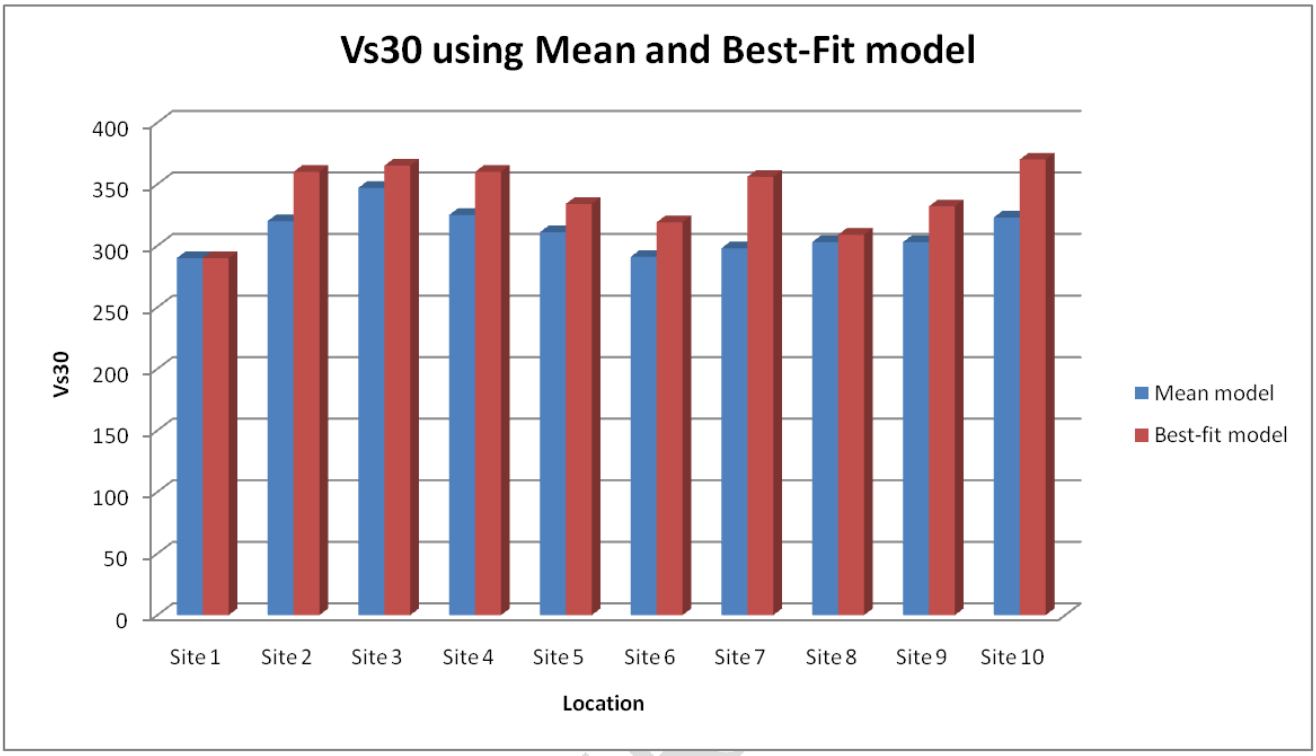

Fig 7 V_s obtained for different sites using mean and the best-fit models