J. Ind. Geophys. Union (May 2018)
v.22, no.3, pp: 265-278

Site characterisation using Multi-channel Analysis of Surface Waves at various locations in Kumaon Himalayas, India

Anand Joshi*[1] and Parul Bhardwaj[2]
[1]Department of Earth Science, Indian Institute of Technology Roorkee, Roorkee, India 247667
[2]KDMIPE, Oil & Natural Gas Corporation Ltd., Dehradun, India 248195
*Corresponding Author: parul1611pandit@gmail.com

ABSTRACT

Local site amplification is greatly influenced by the top 30 m soil column. Rayleigh waves in top soil, acquired by Multi-channel Analysis of Surface Wave (MASW) technique, are helpful in local site amplification studies. In this paper, the acquired data in Kumaon Himalayas are processed for noise elimination and signal enhancement and also for the estimation of shear wave velocity by using "Seisimager" software. We estimated 2D shear wave velocity (V_{s30}) down to 30 m depth in Kumaon region. Average V_{s30} is found to be in the range of 120 - 712 ms^{-1} and average predominant frequency in the range of 1.01 - 5.94 Hz. Estimated average shear wave velocity is used for site classification, which can be used for geotechnical characterization of shallow subsurface formations.

Key words: Shear wave velocity, Predominant frequency, MASW, Kumaon Himalayas

INTRODUCTION

The earthquake ground motions are affected by the source processes, propagation of seismic waves in the medium, and the site characteristics. The study of effects of local site conditions is one of the most vital areas of earthquake engineering. For site classification, V_{s30}, shear wave velocity down to 30 m depth, is a key parameter that characterizes earthquake strong ground motion. The strong ground motion plays an important role in evaluation of seismic hazards in a region. Since 30 m is a typical depth of borings and detailed site characterization in engineering site investigation, most of the site-effect studies in earthquake ground motions are based on the properties in the upper 30 m (Anderson et al., 1996).

The V_{s30} estimate is used to suggest the possible amplification and de-amplification of sites (Dobry et al., 2000). National Earthquake Hazards Reduction Program (NEHRP) provides guidelines for grouping sites into different classes (Borcherdt, 1994; Shafiee et al., 2005; Wen et al., 2008). The current NEHRP approach categorizes soils into A, B, C, D, E and F based on V_{s30} profile, thickness and liquefaction potential (Thitimakorn et al., 2012). The present paper presents a study for estimating the V_{s30} in Kumaon region. MASW method is used to acquire the field data and "Seisimager" software is used for processing and interpretation.

Seismotectonics of the Region

The Kumaon Himalayas lie in the state of Uttarakhand, India and shares its border with Nepal. It falls in the seismic zone V, as per the Seismic Zoning map of India (BIS, 2002). Himalayan fold thrust movement causes high seismic activity in this region. Robust wraps and recurrence of many former faults and thrusts during Quaternary are evident in this region. It falls between the Eurasian plate and Indo-Australian plate, where the stress is constantly getting accumulated giving indications of a potential major earthquake (M>8). Considering the historical earthquakes across these two plates, Kumaon Himalayas are in the central seismic gap. Hence, the shallow subsurface imaging is important for this region.

The location map of this area of study is shown in Figure 1. It also shows location of the broad band stations. Seven stations are tabulated as per the generalised stratigraphy and lithology in Table 1 (Valdiya, 1980).

METHODOLOGY AND DATA

MASW is a non-invasive, non-destructive, and continuous profiling method which efficiently deals with many difficulties related to earthquake engineering. It is widely used for the micro-zonation and site studies. This seismic method is generally utilized for geotechnical characterization of shallow subsurface formations (Park et al., 1999; Xia et al., 1999; Miller et al., 1999). MASW studies have been carried out by several Indian scientists across various parts of India including Jabalpur, Delhi, Ahmedabad and Bangalore (Seshunarayana et al., 2004; Satyam and Rao, 2010; Anbazhagan and Sitharam, 2006; Trivedi et al., 2009). Ariffin et al., (2015) have shown that a combination of active and passive MASW method gives improved results.

In this study, data has been acquired using McSEIS-SX 24 channel digital engineering seismograph with 4.5 Hz geophone array. Geophones are arranged vertically in a

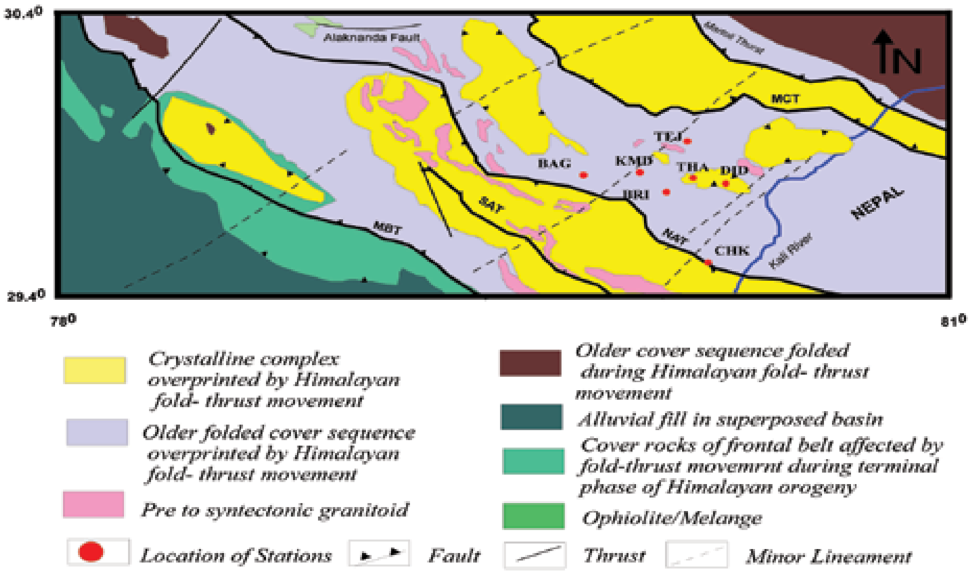

Figure 1. The present area of study belongs to the Kumaon and Garhwal Himalayas, India. MBT = Main Boundary Thrust, MCT = Main Central Thrust, and NAT = North Almora Thrust. Red circles show the location of the stations. Source of the tectonics and geology of the region is as per GSI (2000).

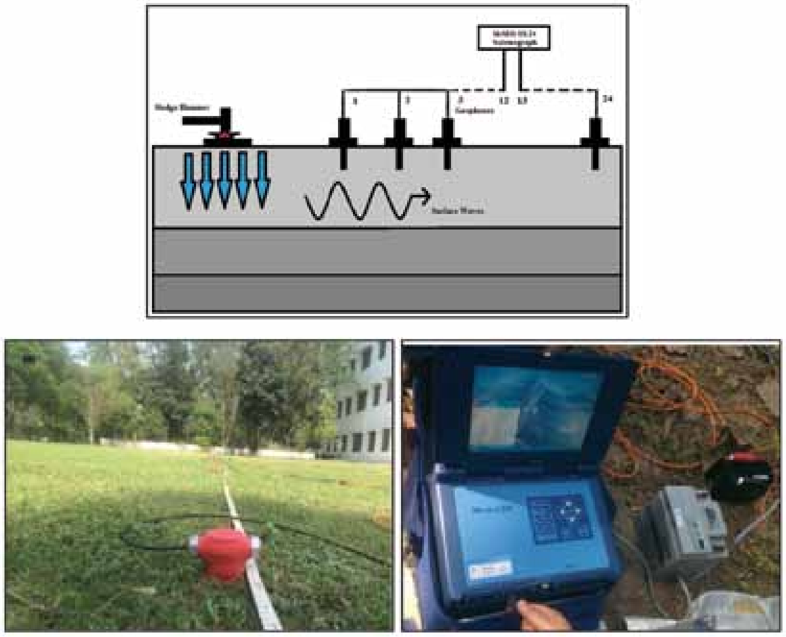

Figure 2. Schematic layout used for data acquisition with McSEIS-SX.

horizontal ground spread. The receiver spacing represents the shortest generated wavelength, which determines the minimum depth to be used in the investigation. In contrast, the spread length of the receiver represents the longest wavelength, which determines the maximum depth to be used in the investigation (Ariffin et al., 2015). During the acquisition, equal geophone and source spacing is considered. The 4.5 Hz geophones are coupled to the seismograph through fixing cables. Seismic waves are generated using mechanical source (hammer 11 kg) and data is recorded in a multi-channel seismograph recorder.

The information of the fundamental mode of Rayleigh waves is used for the generation of dispersion curves by picking the highest energy portion in spectrum to draw curve, which represents the relationship between Rayleigh wave phase velocity and frequency. Raw data for every position is recorded and protected in the apparatus. The raw waveform data obtained has been analysed and processed by the software "Seisimager". Average V_{s30} is estimated using generated 2D shear wave velocity models for all the stations. A schematic layout for data acquisition is shown in Figure 2.

Table 1: Generalised stratigraphy with lithology and age of the locations in Kumaon Himalayas.

Station name	Formation	Lithology	Stratigraphy units	Age
Chaukori	Askot Crystalline	Granite Gneiss, Quartzite, mica-schist and amphibolite	Askot Crystalline	Mesoproterozoic
Kameri Devi	Berinag	Quartzite	Jaunsar Group	Neo-Proterozoic
Tejam	Deoban	Quartzite, Dolomite	Tejam Group	Middle Riphean-Upper Riphean
Thal	Mandhali	Slate, Phyllite and Limestone, Dolomite	Tejam Group	Upper Riphean-Early Vendian
Didihat	Askot Crystalline	Granite Gneiss, Quartzite, mica-schist and amphibolite	Askot Crystalline	Mesoproterozoic
Berinag	Berinag	Quartzite	Jaunsar Group	Neo-Proterozoic
Bhageshwar	Berinag	Quartzite	Jaunsar Group	Neo-proterozoic

Table 2. Name, Code and acquisition parameters of the stations

Station name	Latitude (in degree)	Longitude (in degree)	Station code	Geophone spacing (m)	Source spacing (m)	Spread length (m)
Chaukori	29.52N	80.19E	CHK	2.5	2.5	60
Kameri Devi	29.84N	79.96E	KMD	2.5	2.5	60
Tejam	29.95N	80.12E	TEJ	1	1	24
Thal	29.82N	80.14E	THA	2	2	48
Didihat	29.80N	80.25E	DID	3	3	72
Berinag	29.77N	80.05E	BRI	2.5	2.5	60
Bageshwar	29.83N	79.77E	BAG	2.5	2.5	60

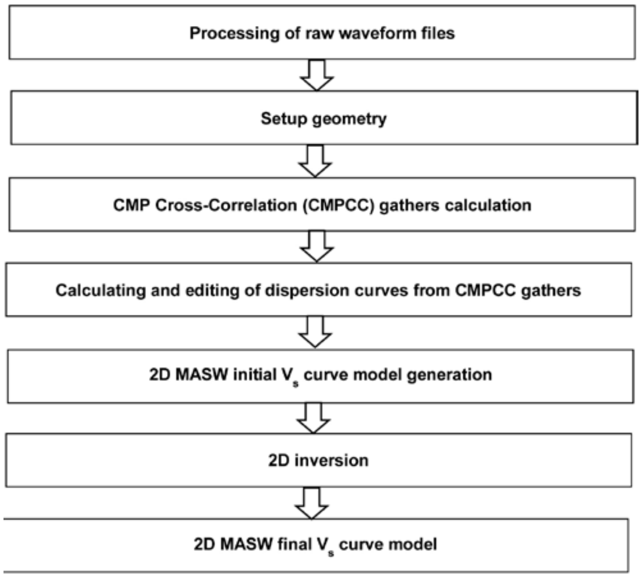

Figure 3. Flowchart depicting the processing steps.

MASW method is applied at various stations in the tough and rocky Kumaon Himalayas, India. The conventional CMP rolling method with 0.01 msec sampling interval has been used. The number of hammering stacks is three and the recording length is 800 msec. 24 geophones were active during the entire survey. Data acquisition parameters of the seven stations are given in Table 2. Geophone spacing varies from 1m to 3m depending on the availability of flat terrain at various stations. Since the said geographical region is highly rugged and rocky, therefore, it is very tough to find a large flat area for the survey. And hence, the survey is conducted on the playgrounds of schools in various localities. This gives an idea about the velocity profile of below mentioned schools.

The creation of dispersion curve is one of the most critical steps for attaining correct shear wave velocity model. 1D shear wave velocity models are calculated using the dispersion curves by using the Least Square Method

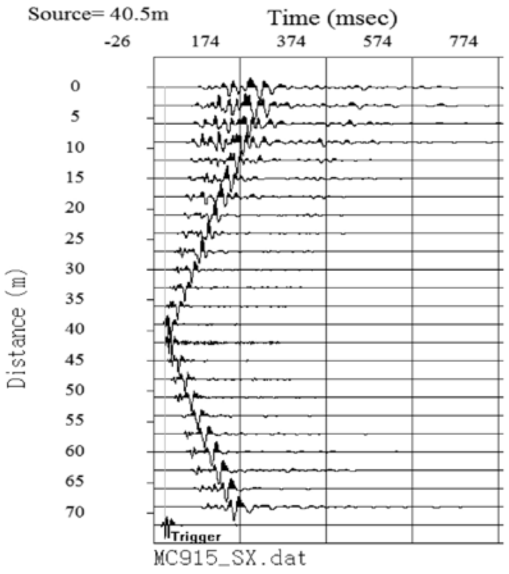

Figure 4. Multi-channel Records (shot gather) in Kumaon Himalayas.

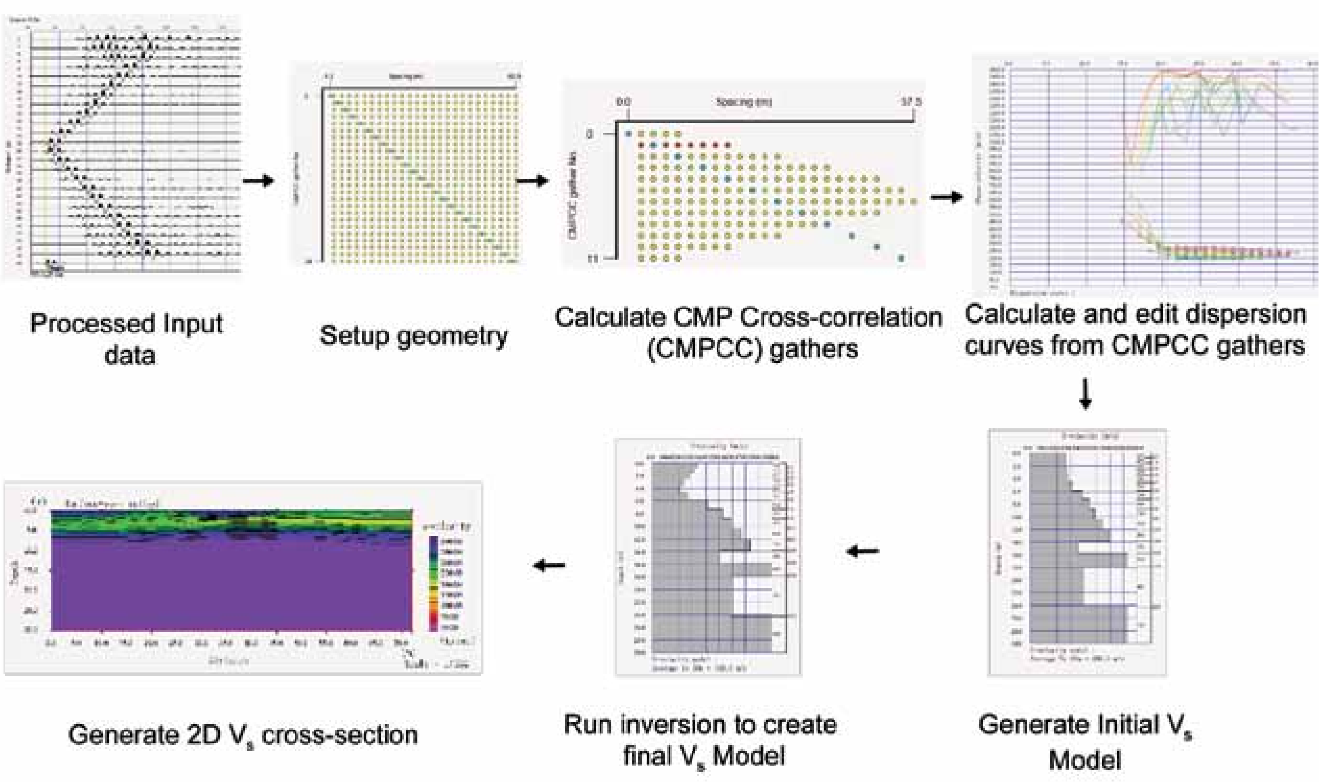

Figure 5. General processing steps used for MASW technique at Didihat Station.

(LSM). As a result, 2D V_{s30} map is constructed. 2D shear wave velocity map is generated using kriging algorithm of interpolation. Flowchart showing the steps of data processing is given in Figure 3 and Figure 5. The raw seismic waveform data is shown in Figure 4.

Common Mid-Point (CMP) gathers and corresponding dispersion curves with initial and final 1D shear wave velocity models at source spacing 0 m, 6 m, 12 m, 18 m, 24 m, 30 m, 36 m, 42 m, 48 m, 54 m, 60 m, 66 m and 72 m are generated for Didihat. The spread length of Didihat is 72 m. This detailed procedure is followed for each station during processing. An example is shown in Figure 6 for source spacing 30 m at Didihat station. Following equation is used to estimate average value of V_{s30}.

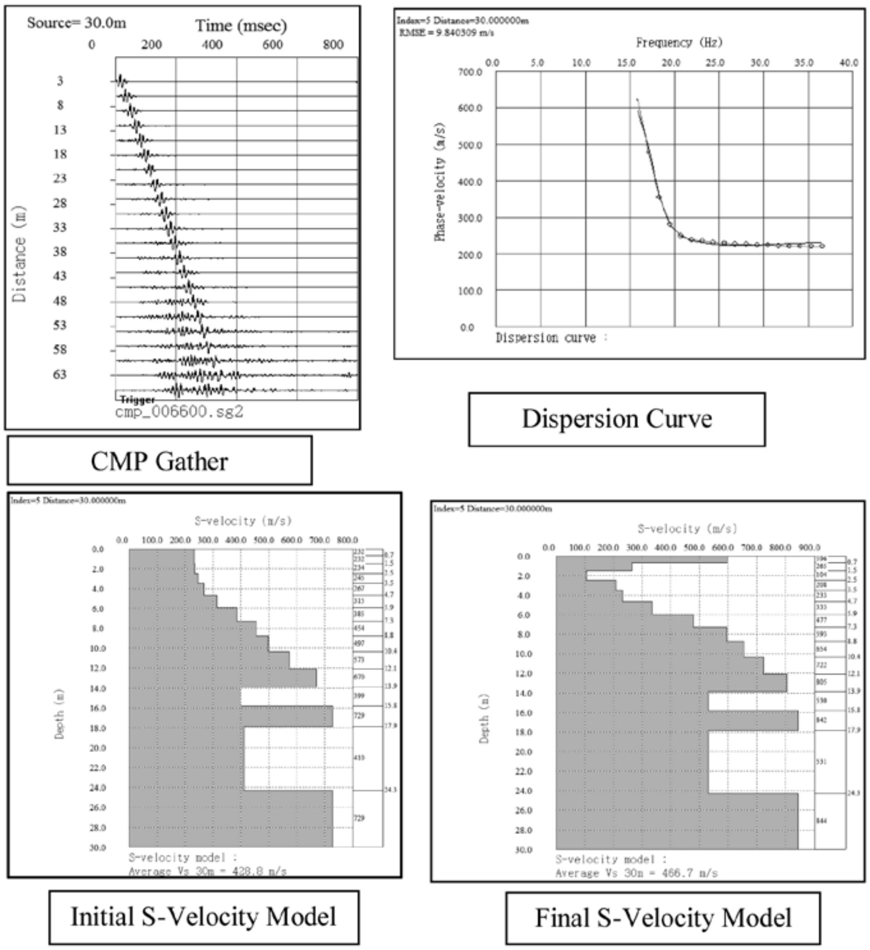

Figure 6. CMP gathers and corresponding Dispersion curve with initial and 2D Shear Wave Velocity Model at Source =30m for Didihat.

$$V_{s30} = \frac{30}{\sum_{i=1}^{n}\left[\frac{h_i}{v_i}\right]} \qquad \text{(Eq. 1)}$$

Where, h_i is the thickness of the i^{th} soil layer in metres; v_i is the shear wave velocity for the i^{th} layer in ms^{-1}, and n is the no. of layers above 30 m.

The predominant frequency is defined as frequency corresponding to the highest value in amplitude spectrum of soil column. It can also be estimated by the following equation:

$$F_p = \frac{V_{s30}}{4h} \qquad \text{(Eq. 2)}$$

Where, F_p is the predominant frequency of the soil column in Hz, V_{s30} is shear wave velocity of the soil column in ms^{-1} and h is the thickness of the soil column i.e. 30 m. The average V_{s30} and predominant frequency of 30 m soil column along with the Root Mean Square Error (RMSE) at various stations in Kumaon Himalayas is tabulated in Table 3.

The RMSE is calculated using following equation

$$RMSE = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N}(d_i^M - d_i^T)\right)} \qquad \text{(Eq. 3)}$$

Where N is the total number of data points and d_i^T and d_i^M are phase velocity of theoretical and measured dispersion curve, respectively. With the successive iterations, the RMSE for shear wave velocity model decreases as shown in Table 3. The RMSE is plotted against the number of iterations for all the stations - depicting the accuracy of the Shear wave velocity profiles generated as shown in Figure 7.

RESULTS AND DISCUSSION

The dispersion curves are extracted by keeping 4.50 Hz as minimum frequency. After processing the dispersion curves, the variation of phase velocity with respect to frequency is calculated. For Didihat, based on phase velocity data

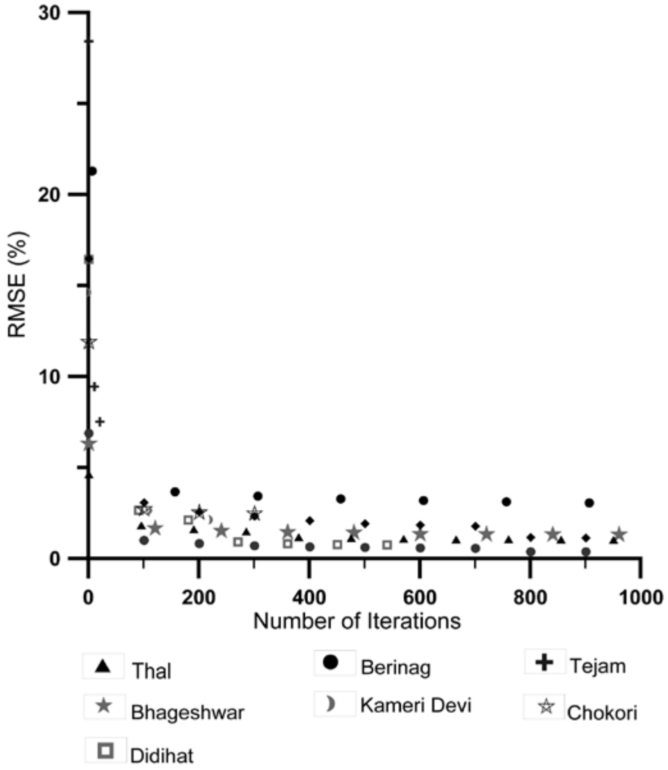

Figure 7. Root Mean Square Error (RMSE) plot against number of iterations at the stations in Kumaon Himalayas.

Table 3. Average Predominant Frequency (PF) of soil column estimated after inversion at various locations in Kumaon Himalayas

Station name	RMSE				Average V_{S30} m	Average PF
	Initial model error		Final model error			
	Velocity (m/s)	RMSE (%)	Velocity (m/s)	RMSE (%)		
Chaukori	99.40	29.00	20.70	2.30	470	3.92
Kameri Devi	42.90	18.40	4.30	1.02	380	3.17
Tejam	27.80	35.80	5.02	7.20	121	1.01
Thal	40.30	6.80	5.40	0.90	524	4.37
Didihat	58.40	18.30	3.60	0.74	486	4.05
Berinag	86.90	15.45	13.75	1.70	712	5.94
Bhageshwar	33.00	7.20	4.60	1.18	409	3.41

obtained in frequency domain, the frequency range is within 14.6 - 37.8 Hz with phase velocity in 200-700 ms^{-1} range. Similarly, the frequency range for Berinag, Tejam, Bageshwar, Kameri Devi, Thal and Chaukori varies from 25.62 - 39.04 Hz, 15.20 - 29.60 Hz, 7.32 - 39.04 Hz, 10.98 - 35.38 Hz, 8.54 - 39.04 Hz and 15.80 - 39.04 Hz and phase velocity varies from 307 - 772 ms^{-1}, 45 - 155 ms^{-1}, 278 - 441 ms^{-1}, 157 - 476 ms^{-1}, 446 - 576 ms^{-1} and 121 - 631 ms^{-1}, respectively.

The results including dispersion curves, 1D velocity models and 2D velocity model are shown for the seven stations in Kumaon Himalayas from Figure 8 to Figure 14. It is observed that geological setting and lithology of the area play a major role on predominant frequency. Estimated predominant frequencies, derived using equation 2, vary from 3.92 - 4.05 Hz for the granitic and gneissic rocks, 3.17 - 5.94 Hz for the quartzite rocks, 1.01 Hz for quartzite along with dolomite rocks and 4.37 Hz for the slates, phyllites along with limestones and dolomite.

High-rise buildings typically have low natural frequency as compared to small buildings. Kumaon region is mostly populated with small to medium buildings. It is observed that Predominant Frequency in this region varies from 1.01 to 5.94 Hz indicating a wide range of damaging pattern to various structures in the region. Estimated Predominant Frequency is 1.01 Hz at Tejam, which corresponds to

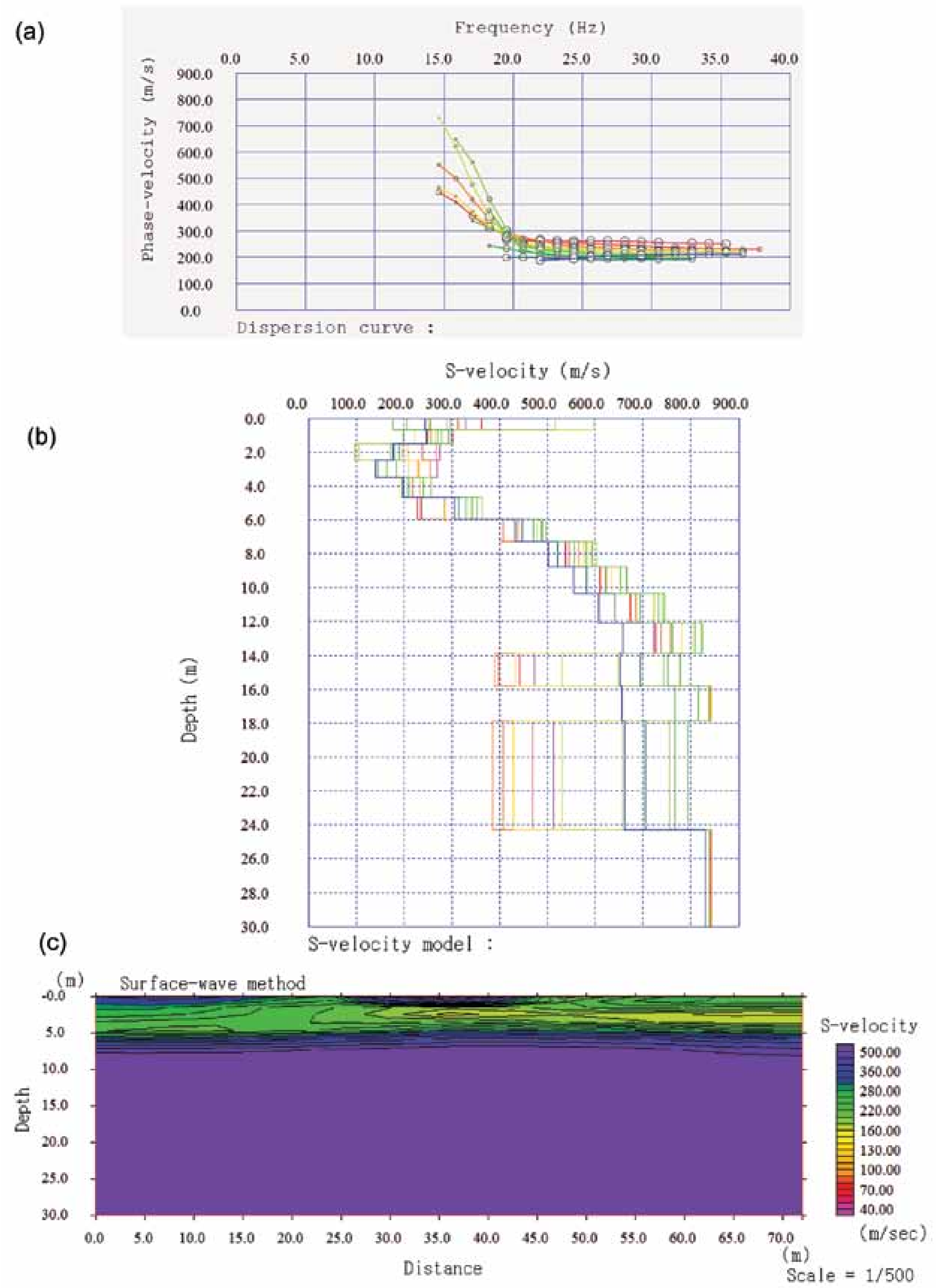

Figure 8. The results obtained at Didihat station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted using trends in (a), and (c) 2D Shear Wave Velocity Model.

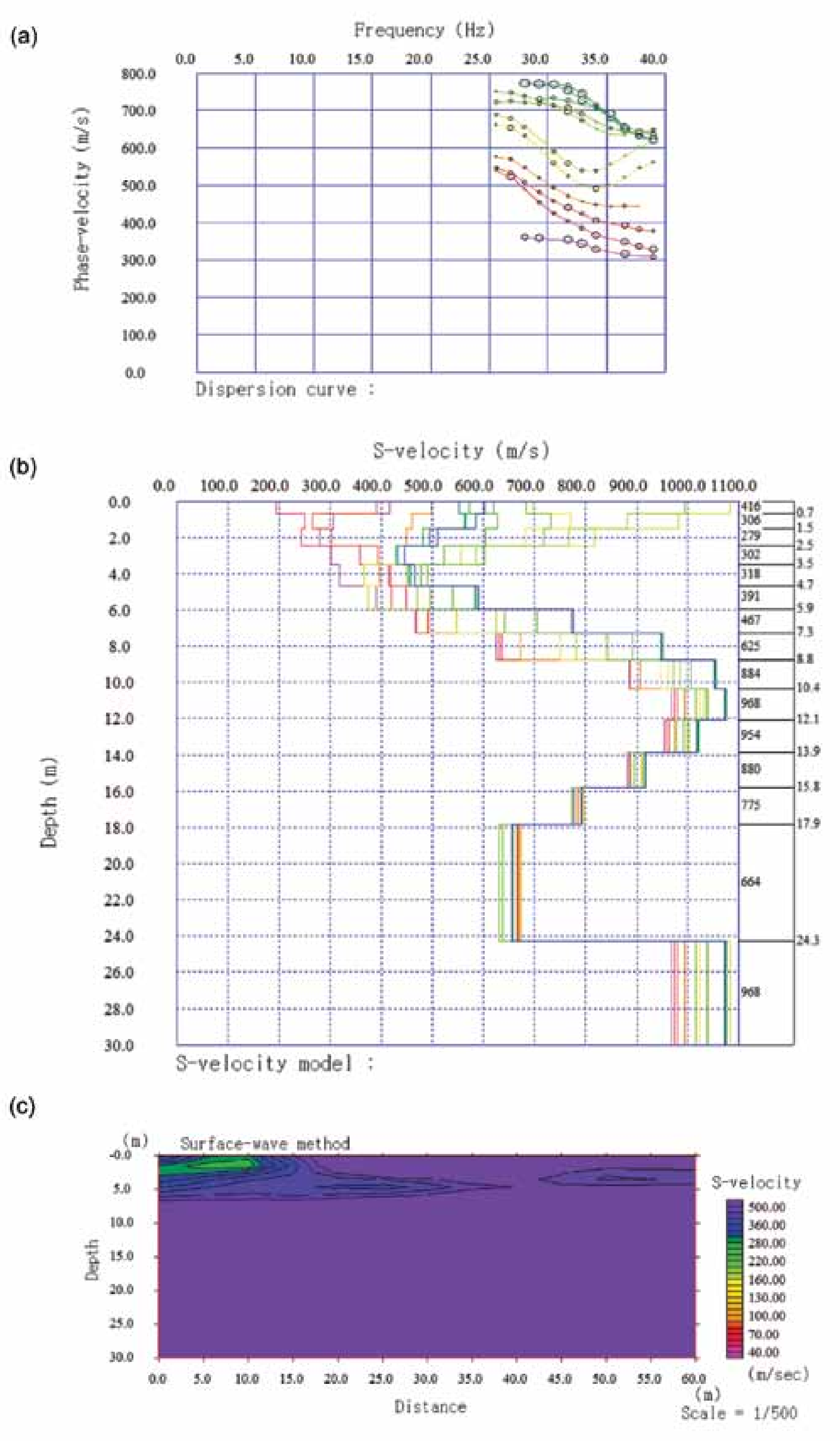

Figure 9. The results obtained at Berinag station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted using trends in (a), and (c) 2D Shear Wave Velocity Model.

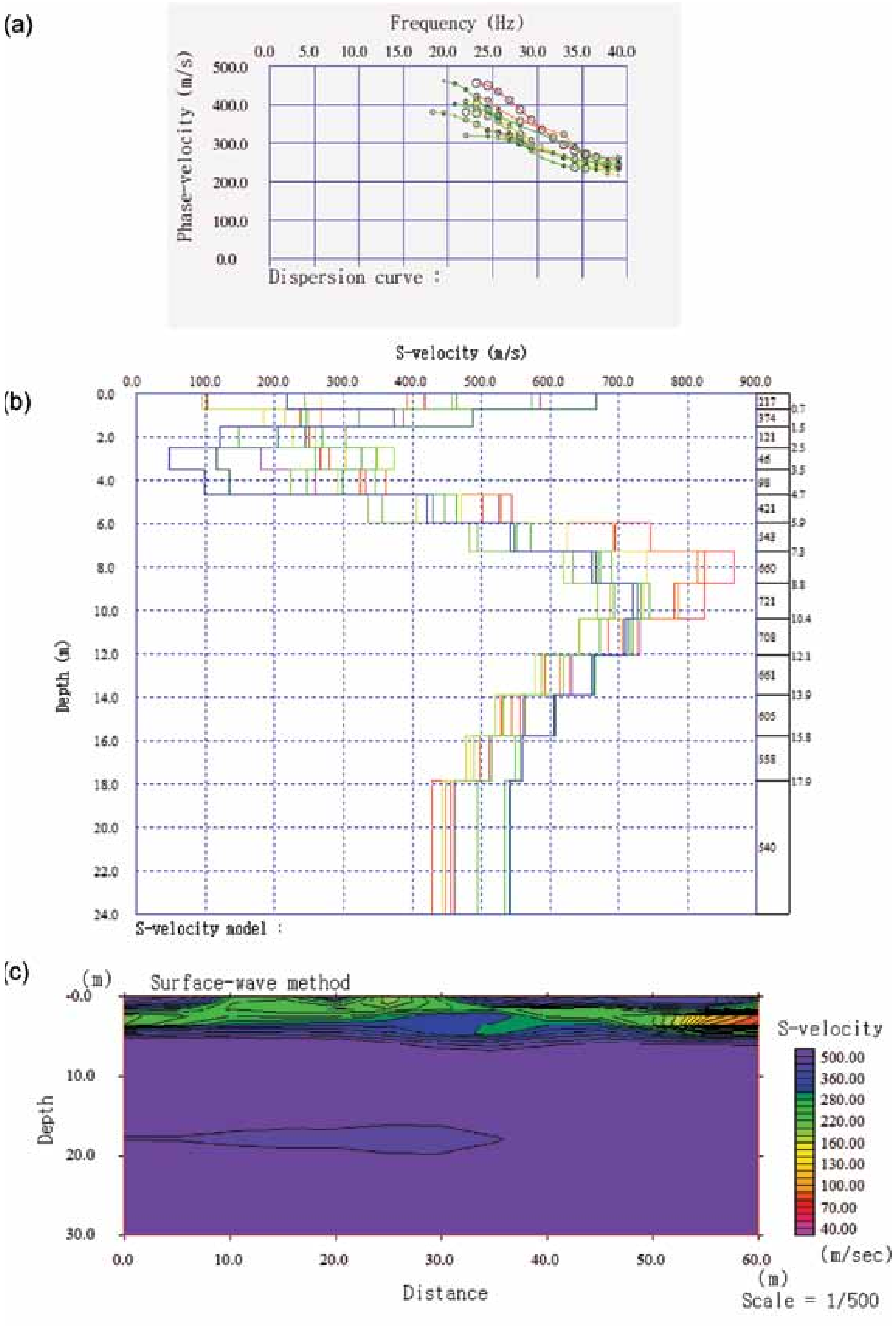

Figure 10. The results obtained at Chaukori station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted using trends in (a), and (c) 2D Shear Wave Velocity Model.

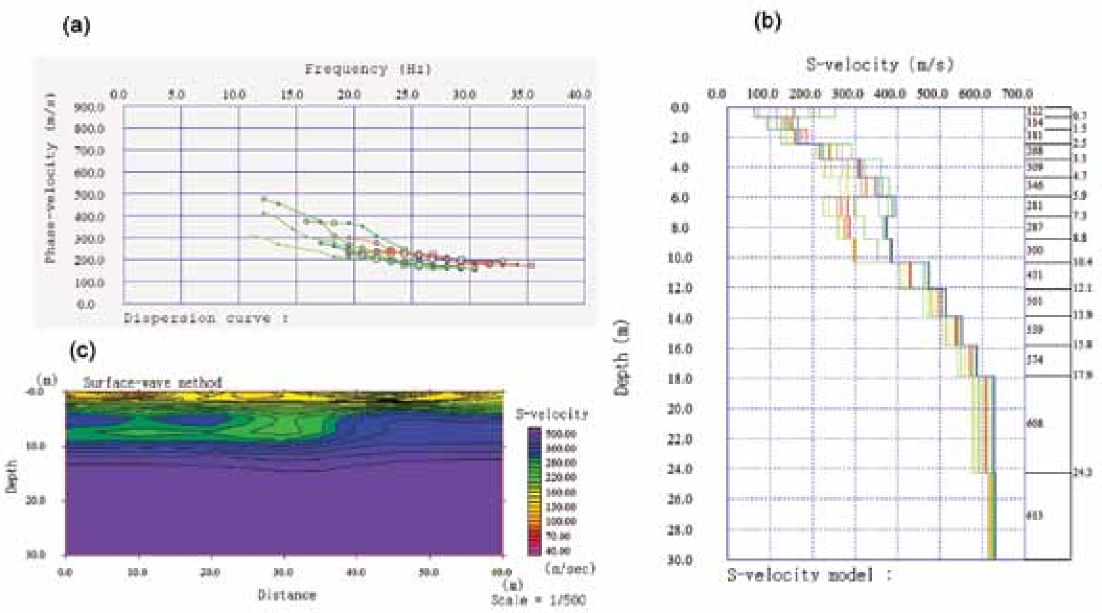

Figure 11. The results obtained at Kameri Devi station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted using trends in (a), and (c) 2D Shear Wave Velocity Model.

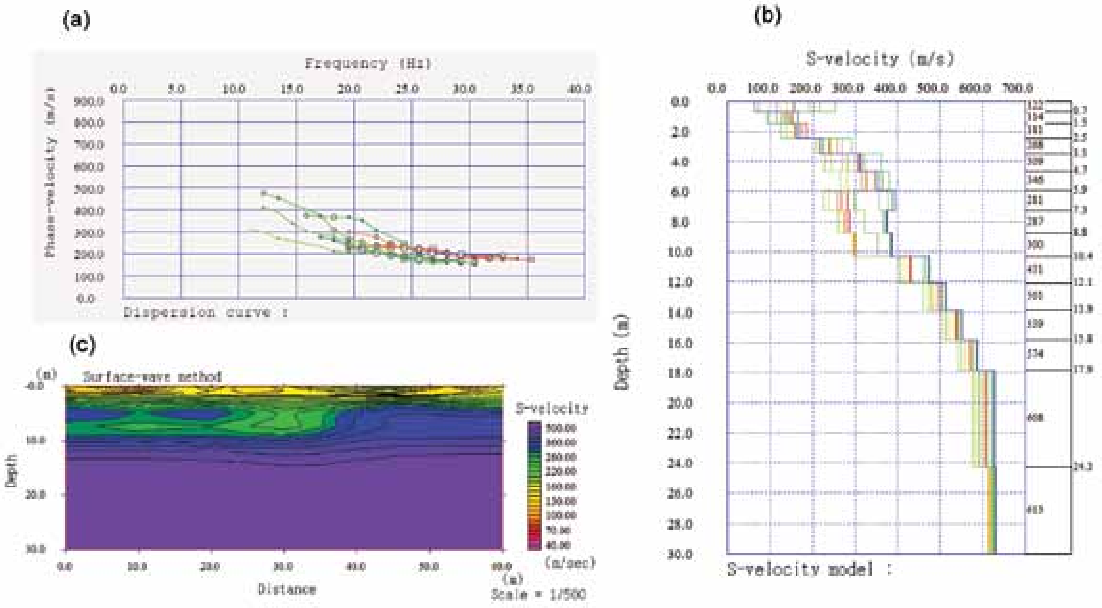

Figure 12. The results obtained at Bhageshwar station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted using trends in (a), and (c) 2D Shear Wave Velocity Model.

Proterozoic crystalline formations containing quartzite and dolomitic limestones with bands and intercalations of limestones. The estimated Predominant Frequency is 5.94 Hz at Berinag, which corresponds to quartzite rocks. The higher estimated Predominant Frequency at various locations is hazardous to small buildings.

Chaukori village is located in Berinag tehsil of Pithoragarh district of Uttarakhand. It is 86 Km away from district Pithoragarh at an elevation of ± 2010 m. Stratigraphically, it falls in Askot Crystalline. The Askot Crystalline consists of granite and gneisses. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 15.80 - 39.04 Hz and the range of phase velocity is 121-631 ms^{-1}. The average shear wave velocity of Chaukori is 470 ms^{-1}, hence it can be classified as class C i.e. very hard soil and soft rock category. Its estimated average predominant frequency is 4 Hz.

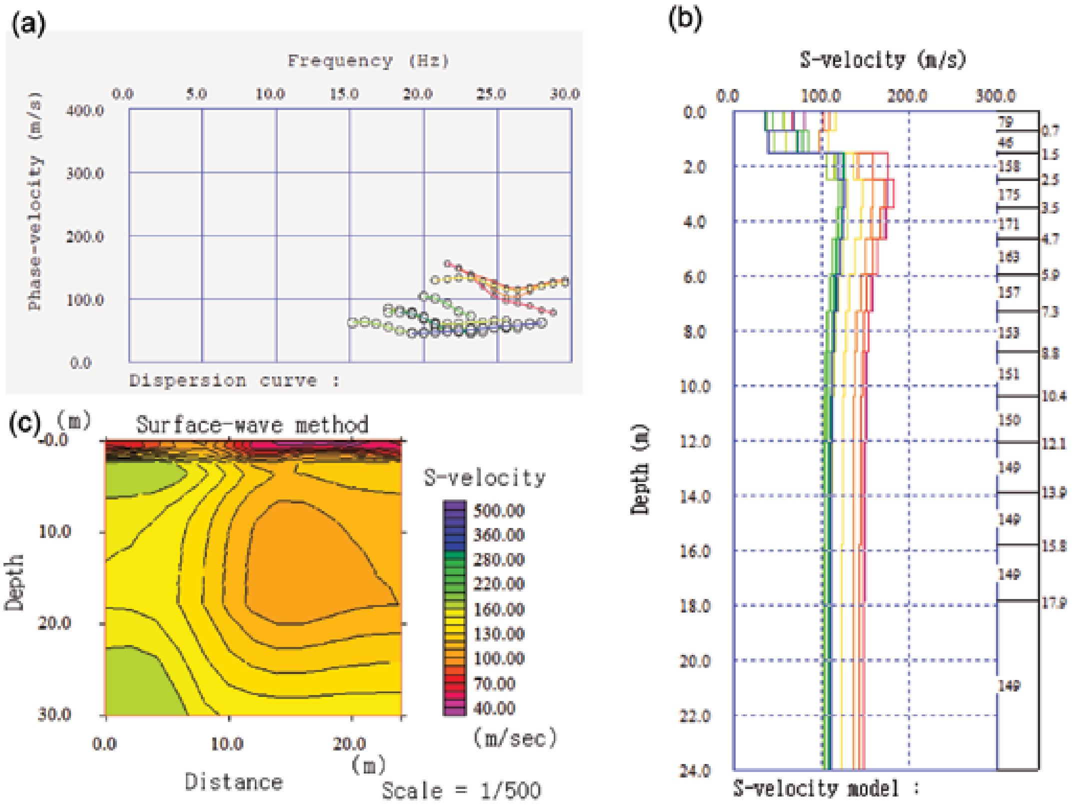

Figure 13. The results obtained at Tejam station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted using trends in (a), and (c) 2D Shear Wave Velocity Model.

Granite and gneisses are moderately suited for high rise structures such as dams and multi-storey buildings and the site is more appropriate for low height buildings e.g. schools, primary health centers etc.

Kamedidevi is famous for the temple of goddess Shakti, situated in Bhageshwar district of Uttarakhand. Stratigraphically, it forms the part of Berinag Formation of Jaunsar Group having quartzite as lithological unit. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 11.0 - 35.0 Hz and the range of phase velocity is 157 - 476 ms $^{-1}$. The average shear wave velocity of Kamedidevi is 380 ms^{-1}, hence it can be classified as class C i.e. very hard soil and soft rock category. Its estimated average predominant frequency is 3 Hz.

Quartzite type of rocks was profiled in this study and significant differences were found in near-surface velocity. This explains part of the measured differences in site amplification. The rock sites are located in average shear wave velocity of 380 ms^{-1}, which are quite significant for low rise buildings rather than high rise buildings.

Tejam village is located in Munsiari tehsil, 74 km away from district Pithoragarh. Stratigraphically it forms the part of Deoban Formation of Tejam Group having quartzite and dolomite as lithological units. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 15.0 – 29.5 Hz and the range of phase velocity is 45 - 155 ms^{-1}. The average shear wave velocity of Tejam is 121 ms^{-1}, hence it can be classified as class E i.e. soft clay category. Its estimated average predominant frequency is 1 Hz. The results reveal that the quartzite inter-bedded with dolomite is not good for high rise structures and multi-storey buildings, however the site is more suited for low rise buildings e.g. weirs, barrages etc.

Thal village lies in Pithoragarh district of Uttarakhand at an elevation of 784 m above mean sea level. It is located 245 km from the state capital Dehradun. It belongs to Mandhali Formation of Tejam Group. The rocks exposed are slate, phyllite, limestone and dolomite. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 8.5 - 39.0 Hz and the range of phase velocity is 446 – 576 ms^{-1}. The average shear wave velocity of Thal is 524 ms^{-1} hence it can be classified as class C i.e. very hard soil and soft rock category. Its estimated average predominant frequency is 4 Hz.

Didihat is a busy township in Pithoragarh and is situated at the hill top plains of Digtarh-Bhadigad with Charamgad River flowing below the town. Stratigraphically it falls in Askot Crystalline. The Askot Crystalline is mainly composed of granite and gneisses with some traces of mica-

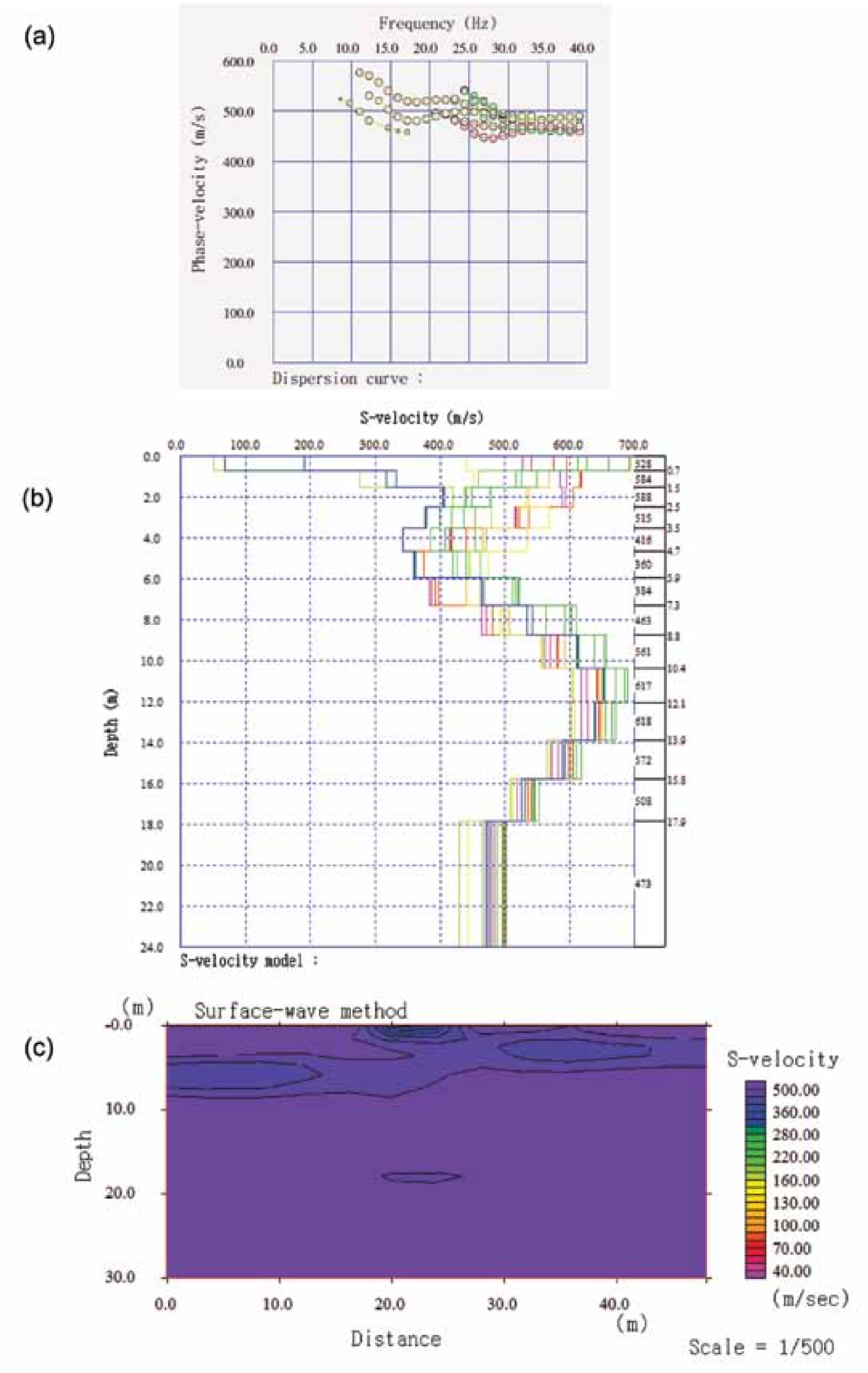

Figure 14. The results obtained at Thal station (a) dispersion curve obtained from processed record, (b) 1D Shear Wave Velocity Model inverted from trends in (a), and (c) 2D Shear Wave Velocity Model.

Table 4. NEHRP site classes (BSSC, 2003)

Site classification	Description	Average shear wave velocity up to 30 m (V_{s30})
A	Very hard rocks	>1500
B	Rocks	$760 < V_{s30} < 1500$
C	Very hard soil and soft rock	$360 < V_{s30} < 760$ Or $N > 50$, $S_u > 100$ Kpa
D	Hard soil (sands, clays and gravels)	$180 < V_{s30} < 360$ or $50 > N > 15$, $100 > S_u > 50$ Kpa
E	Soft clay of thickness about H in site profiles	$V_{s30} < 180$ or $H > 3$m(PI > 20), w > 40%, $S_u < 25$ Kpa
F	Soils requiring site – specific evaluations	

H: Thickness; S_u: Undrained Shear Strength; N: Standard Penetration Test Blow Count PI: Plasticity Index; w: Water Content

schist and amphibolite. It is located at an elevation of 1725 m. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 14.5 - 38.0 Hz and the range of phase velocity is 200-700 ms^{-1}. The average shear wave velocity of Didihat is 486 ms^{-1}, hence it can be classified as class C i.e. very hard soil and soft rock category. Its estimated average predominant frequency is 4 Hz.The results reveal that the lithology like granite and gneisses with some traces of mica-schist and amphibolite is not good for high rise structures and multi-storey buildings without proper strengthening of material, however the site is more suited for low rise buildings e.g. weirs, barrages etc.

Berinag is situated 160 km from Nainital in Pithoragarh district, Uttarakhand. It gets its name from temple situated at the top of Berinag hill. It is located at an elevation of 1860 m from mean sea level. Stratigraphically it falls in Berinag Formation of Jaunsar Group. The rock exposed is mostly quartzite of Neo-Proterozoic age. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 26 - 39 Hz and the range of phase velocity is 307 – 772 ms^{-1}. The average shear wave velocity of Berinag is 712 ms^{-1}, hence it can be classified as class C i.e. very hard soil and soft rock category. Its estimated average predominant frequency is 6.0 Hz.

This type of lithology mostly having quartzite is suitable for the construction of high rise structures such as dams and buildings, however the site is perfectly suitable for moderately to low height buildings e.g. schools, primary health centers etc.

Bhageshwar is well known for its scenic beauty, glaciers, rivers and temples. It is located on the confluence of Sarju and Gomati rivers. It is having rocks of Berinag Formation of Jaunsar Group. Quartzite of Neo Proterozoic age is exposed in this area. Based on the phase velocity data obtained in frequency domain; the estimated frequency range is within 7.0 - 39.0 Hz and phase velocity is within the range of 278 -441 ms^{-1}.

The average shear wave velocity of Bhageshwar is 409 ms^{-1}, hence it can be classified as class C i.e. very hard soil and soft rock category. Its estimated average predominant frequency is 3.0 Hz. This type of lithology mostly having quartzite is averagely suited for construction of high rise structures such as dams and buildings, however the site is perfectly suited for moderately to low rise buildings e.g. schools, primary health centers etc.

According to the site classification by NEHRP, the stations lie in C and E classes as shown in Table 4. Bageshwar, Chaukori, Thal, Berinag, Kameri Devi and Didihat lie in class C with hard to very hard soil category. Tejam with shear wave velocity 120 ms^{-1} is categorised under class E of soft clay category.

CONCLUSION

MASW technique is a non-destructive method to measure shear wave velocity and is useful to measure shear wave velocity in an urban region. This technique gives a 2D shear wave velocity model with depth, which can easily be interpreted. This seismic experiment has given an important information about the velocity model of the various localities in Kumaon Himalayas. Attained 1D and 2D velocity models help in the soil classification in terms of Predominant Frequencies, average shear wave velocities and depth of various layered units. Shear wave velocity increases with depth due to greater degree of compaction and central crystalline formation present in the region. Soil classification is carried out on the basis of the results obtained in terms of average shear wave velocity; showing the importance of study in geotechnical engineering studies. Such analysis could be done for other sites of the Himalayas as well, to obtain the better image of the subsurface structure. Velocity information is also important for simulation of earthquake strong ground motions.

ACKNOWLEDGEMENTS

The authors place on record their sincere thanks to Director (Exploration), ONGC, for his kind permission to publish this work. The authors are thankful to Mr. S.K. Das, Ex-Executive Director, ONGC and Dr. Dinesh Kumar, Professor, Kurukshetra University, Kurukshetra for their valuable suggestions and constructive comments. The views expressed in this work are solely of the authors and do not necessarily reflect the views of ONGC. The work presented in this paper is an outcome of the sponsored project from Department of Science and Technology (DST), Government of India with project reference no. SR/S4/ES-596/2011 and SER-1136-ESD/17-18. Thanks are due to Dr. B.K. Rastogi for useful suggestions. The authors thankfully acknowledge for final refinement and editing by Dr.P.R.Reddy.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

REFERENCE

Anbazhagan, P., and Sitharam, T.G., 2006. Evaluation of Dynamic Properties and Ground Profiles using MASW: Correlation between Vs and N60, 13th symposium of Earthquake Engineering, Indian Institute of Technology, Roorkee, Paper No. 2008.

Anderson, J.G., Lee, Y., Zeng, Y. and Day, S., 1996. Control of Strong Motion by the Upper 30 Meters, Bulletin of the Seismological Society of America, v.86, pp: 1749-1759.

Ariffin, J., Ismail, M.A.M., Tan, C.G., and Murtadza, N.M., 2015. Site Characterization of Marine Clay Deposits in South Seberang Prai, Penang using Combined Active and Passive Multichannel Analysis of Surface Wave (MASW). Soft Soil Engineering International Conference 2015 (SEIC2015) IOP Conf. Series: Materials Science and Engineering, doi:10.1088/1757-899X/136/1/012032.

B.I.S., 2002. Indian standard criteria for earthquake resistant design of structures, IS 1893: (Part 1) 2002, Part 1 General Provisions and Buildings (Fifth Revision), Bureau of Indian Standards, New Delhi.

Borcherdt, R.D., 1994. Estimates of site-dependent response spectra for design (methodology and justification). Earthquake Spectra v.10, pp: 617– 653.

Building Seismic Safety Council, 2003. NEHRP Recommended Provisions for seismic Regulations for New buildings and other Structures, Part1: Provisions, FEMA 368, Federal Emergency Management Agency, Washington, D.C.

Dobry, R., Borcherdt, R.D., Crouse, C.B., Idriss, I.M., Joyner, W.B., Martin, G.R., Power, M.S., Rinne, E.E. and Seed, R.B., 2000. New site coefficients and site classification system used in recent building seismic code provisions. Earthquake Spectra, v.16, pp: 41- 67.

Miller, R.D., Xia, J., Park, C.B., and Inanov, J.M., 1999. Using MASW to map bedrock in Olathe, Kansas. Society Exploration Geophysics., pp: 433-436.

Park, C.B., Miller, R.D., and Xia, J., 1999. Multichannel analysis of surface waves (MASW).Geophysics, v.64, pp: 800–808.

Satyam, D.N., and Rao, K.S., 2010. Multi-Channel Analysis of Surface Wave (MASW) testing for Dynamic site characterization of Delhi region, 5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and soil dynamics, San Diego, California, I, pp: 327-330.

Seshunarayana, T., and Sundararajan, N., 2004. Evaluation of 5th Conference & Exposition on Petroleum Geophysics. Hyderabad-2004, India, pp: 642-646.

Shafiee, A., and Azadi, A., 2006. Shear-wave velocity characteristics of geological units throughout Tehran City, Iran. Journal of Asian Earth Sciences.

Thitimakorn, T., and Channoo, S., 2012. Shear Wave Velocity of Soils and NEHRP Site Classification Map of Chiangrai City, Northern Thailand. Electronic Journal of Geotechnical Engineering, v.17, pp: 2891-2894.

Trivedi, S.S., Rao, K.S., Gupta, K.K., and Rathod, G.W., 2009. Mapping average shear wave velocity for Ahmedabad soil sites: A case study. IGC, Guntur, India.

Valdiya, K.S., 1980. Geology of Kumaun Lesser Himalaya, Interim Record: Dehradun. Wadia Institute of Himalayan Geology, pp: 289.

Wen, R., Shi, D., and Ren, Y., 2008. Site Classification based on Geological Genesis and its application. The 14th World Conference on Earthquake Engineering, Beijing, China.

Xia, J., Miller, R.D., and Park, C.B., 1999. Estimation of near-surface shear wave velocity by inversion of Rayleigh waves. Geophysics, v.64, pp: 691-700.

Received on: 23.10.17; Revised on: 19.1.18; Re revised on: 2.2.18; Accepted on: 10.2.18