Seismic site classification of Itanagar city, India, considering spatial variation of shear wave velocity obtained using extensive active MASW survey

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Abstract: This study presents an advanced seismic site characterization for Itanagar, Arunachal Pradesh, situated within India's highly seismically active Himalayan belt. The research addresses critical limitations associated with traditional V_{s30}-based seismic site classifications, highlighting the necessity of incorporating detailed spatial variations of subsurface shear wave velocity (SWV) profiles. Employing Multichannel Analysis of Surface Waves (MASW), SWV data were collected at 22 selected locations, covering diverse geological terrains throughout the city. The MASW methodology involved field data acquisition, dispersion analysis, and inversion to obtain accurate SWV profiles up to 30 m depth. The analysis revealed significant heterogeneity in soil stratification, challenging the reliability of V_{s30}-based site classifications, particularly for sites exhibiting notable subsurface layer variability. The study demonstrates that relying solely on V_{s30} values can lead to underestimation or overestimation of seismic response, especially in complex geological environments. To address this, the research introduces an alternative approach of computing average SWV values over discrete 5 m depth intervals, providing a clearer and more realistic depiction of subsurface conditions. This innovative approach better captures soil stiffness variations and their implications for seismic wave amplification. Spatial distributions of SWV were visualized through contour maps, effectively delineating areas with potentially higher seismic amplification risks. Results indicate predominant site classes of C and D under NEHRP guidelines, characterized by medium to dense soils and soft rocks. This refined classification methodology advocates for more accurate site-specific seismic evaluations, emphasizing the importance of detailed subsurface characterization.

Keywords: Seismic site characterization, Active MASW survey, Shear wave velocity, NEHRP site classification, Contour maps

1. Introduction

Earthquakes are among the most devastating natural phenomena, capable of triggering multi-hazard events that cause widespread destruction. Historical and recent seismic events, such as the 8.1 M_w Assam earthquake (1897), 7.9 M_w Kanto earthquake (1923), 6.9 M_w El-Centro earthquake (1940), 9.5 M_w Chili earthquake (1960), 7.5 M_w Niigata earthquake (1964), 6.9 M_w Kobe earthquake (1995), 7.7 M_w Bhuj earthquake (2001), 6.3 M_w Christchurch earthquake (2011), 9.0 M_w Japan-Tohoku earthquake (2011), 7.8 M_w Nepal earthquake (2015) and 7.8 M_w Turkey-Syria earthquake (2023), 7.6 M_w Taiwan earthquake (2024), have demonstrated severe impacts on livelihoods and regional economies, underscoring the critical importance of understanding seismic hazards. These hazards manifest through ground shaking, soil liquefaction, lateral spreading, tsunamis etc., with the dynamic behavior of subsurface soil playing a key role in governing these effects. Consequently, geotechnical engineers must accurately assess the dynamic characteristics of soil to design earthquake-resistant structures and determine appropriate site-specific seismic design parameters (Dobry *et al.* 2000). The shear wave velocity (SWV) of soil, which is an indicator of soil stiffness, is characterized as a key parameter in the seismic ground response analysis (Kumar *et al.* 2018; Kumar and Kumar 2023; Kumari *et al.* 2024). In recent times, application of Multichannel Analysis of Surface Wave (MASW) technique has gained profound popularity among geotechnical engineers to identify the subsurface stratification (Park *et al.* 1999; Xia *et al.* 1999; Xia *et al.* 2002; Foti *et al.* 2018; Baglari *et al.* 2020). MASW is a non-destructive geophysical technique to decipher the shear wave velocity profile of the substrata that eventually aids in the geotechnical site characterization. This technique analyzes the dispersion characteristics of fundamental mode of surface wave (namely, Rayleigh wave) propagating horizontally along the ground surface from impact source to a receiver array (Taipodia and Dey 2018a). Several successful studies are available worldwide to characterize the soil profile based on MASW, thereby establishing the technique as a very effective and efficient one in detecting the SWV profile of the subsurface (Mahajan and Kumar 2020; Taipodia *et al.* 2020a; Ayele *et al.* 2022; Imam *et al.* 2022, 2023). Literatures revealed that the estimation or the development of site/region-specific SWV profile is significantly important to identify the soil-site characteristics and the same can be further utilized for the region-specific ground response studies. Traditionally, the seismic site response has been evaluated using the shear wave velocity (SWV) within the upper 30 meters of soil (V_{s30}). However, reliance on a single averaged value over 30 meters can overlook critical variations in subsurface layers, particularly in regions with significant stratigraphic heterogeneity (Nadi *et al.* 2020; Zhong *et al.* 2024). This limitation is particularly concerning in areas prone to liquefaction, such as those classified as site classes E and F, where detailed subsurface investigations are crucial (NEHRP, 2020). Recent advances in geophysical techniques, notably the Multichannel Analysis of Surface Waves (MASW), offer a more refined approach to seismic site characterization. MASW enables the detailed profiling of subsurface shear wave velocities, capturing the spatial variation of SWV across different layers. This approach provides a more accurate representation of the seismic behavior of site, particularly in regions with complex subsurface conditions where V_{s30} may not adequately reflect the site classification or capture the site-specific seismic response.

In light of these considerations, this study aims to move beyond the conventional V_{s30}-based concept of site classification and focus on the ground response analysis based on the spatial variation of SWV profiles obtained through MASW. The present research is centered on Itanagar, the capital city of Arunachal Pradesh, India, a region located in the highest seismic zone (Zone-V) but lacking comprehensive seismic studies. As Itanagar is undergoing significant infrastructural development under the Smart City initiative, understanding the seismic response of the region becomes increasingly critical. This study provides a pioneering assessment of Itanagar's subsurface SWV profiles, offering insights into the seismic amplification potential of the region. By addressing the limitations of V_{s30} and emphasizing the importance of spatial SWV variations, this research proposes a more realistic approach to seismic site characterization. The findings are intended to inform the design and planning of resilient infrastructure in Itanagar, contributing to the broader field of geotechnical earthquake engineering. This study highlights the necessity of advancing from the V_{s30}-based approach to achieve accurate and reliable seismic hazard assessments, which are essential for safeguarding both existing and future structures.

2. Seismic Site Classification based on V_{s30} and microzonation of Indian cities

Seismic site characterization requires the assessment of soil properties, either in terms of SWV or shear modulus, to foresee the potential influence of seismic motions on soil and vice-versa for future earthquakes. In order to achieve the precise estimation of design parameters, seismic site characterization must be properly conducted with due incorporation of the geotechnical, geological, seismological as well as seismo-tectonic aspects. It is well established that near-surface soil layers significantly influence seismic wave characteristics especially the amplitude and frequency content parameters (Kramer, 1996). In this regard, several researchers have revealed that SWV is one of the most important parameters for site-specific seismic response study (Boore and Joyner 1997; Presti *et al.* 2004). Accordingly, several researchers have used active MASW technique to identify seismic characteristics of a site in terms of SWV profiles that is further used to assess the representative average shear wave velocity within a depth of 30 m from the ground surface (i.e., V_{s30}). The average SWV over any depth H from the ground surface is defined as V_H, as expressed in Eqn. (1)

$$V_H = \frac{\sum h_i}{\sum\left(\frac{h_i}{v_{si}}\right)} \tag{1}$$

where h_i is the thickness of individual soil layers up to the cumulative depth $H = \Sigma h_i$ and v_{si} is the shear wave velocity of the corresponding individual layers. In the same line of assessment, if the significant depth of soil profile is considered to be 30 m, the corresponding average SWV for a depth of the first 30 m is represented as V_{s30} (Borcherdt, 1994), and is expressed as:

$$V_{S30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{h_i}{v_{si}}\right)} \tag{2}$$

where, N is the number of individual soil layers within the depth of 30 m. The V_{s30} parameter, as recommended by the National Earthquake Hazard Reduction Program (NEHRP, 2020), has been widely used to classify sites into various categories for seismic design. According to the updated guidelines (NEHRP, 2020), depending on V_{s30}, apart from soil sites being classified into six classes as earlier (namely site class A, B, C, D, E and F), additional three new site classes (BC, CD and DE) are introduced to provide better insight of the site shear wave velocity classes as shown in Table 1.

The Department of Science and Technology (DST), Government of India, had initiated microzonation of 63 cities at the national level (Bansal and Vandana, 2007), some of which have been completed while others are still in progress. Under this flagship program, several researchers have successfully conducted MASW-based geophysical investigation for many cities of India; some of the important ones are referred herein in Table 2.

Table 1 Site classification based on site-specific conditions established by NEHRP (2020)

Site Class	Soil profile description	NEHRP (2020) V_{s30} (m/s)
A	Hard rock	> 1500
B	Medium hard rock	> 900 to 1500
BC	Soft rock	> 700 to 900
C	Very dense sand or hard clay	> 480 to 700
CD	Dense sand or very stiff clay	> 330 to 480
D	Medium dense sand or stiff clay	> 230 to 330
DE	Loose sand or medium stiff clay	> 170 to 230
E	Very loose sand or soft clay	< 170
F	Soils requiring site response analysis as per Section 21.1	Ref. Section 20.2.1

It is worth mentioning that there are no such seismic site classification studies available for Itanagar city, Arunachal Pradesh, and given that the city is deemed to be a smart city as per the decree of the Government of India, it is high time that such site classification study is conducted for the capital city, and the same is reported in this paper.

3. Study Area and Test Locations

Figure 1 presents the study area ‘Itanagar City’, which is the capital of Arunachal Pradesh spread over the area of 51.69 km^2. It is located at latitude of 27.06°N to 27.11°N and longitude of 93.58°E to 93.62°E. The study area is characterized by rugged hilly terrain of low relief with altitudes varying from minimum of 80 m to a maximum of 1540 m having highly undulation terrain and uneven topography (Singh, 2007). This area has also experienced heavy rainfall during monsoon with average rainfall ranging from 646 mm to 726 mm. Figure 1 also shows the test locations where MASW tests were conducted to identify the SWV profile.

Table 2 A summary of site characterization for Indian cities based on SWV from MASW tests

References	**City**	**V_s / Site-classes**
Pandey *et al.* (2016)	Delhi	V_s - 185 to 565 m/s Site class C and D
Anbazhagan and Sitharam (2008)	Bengaluru	Site class D
Mahajan (2009)	Dehradun	Site class C, D and E
Maheswari *et al.* (2010)	Chennai	Site class D
Mahajan *et al.* (2011)	Dhanauri, Roshnabad	V_s - 508 to 1059 m/s
Rao *et al.* (2011)	Jabalpur	V_s - 250 to 750 m/s
Sairam *et al.* (2011)	Gandhinagar, Gujarat	Site class C and D
Trupti *et al.* (2012)	Coastal Andhra Pradesh	V_s - 100 to 250 m/s
Mahajan *et al.* (2012)	Jammu	V_s - 238 to 450 m/s
Sil and Sitharam (2014)	Agartala	Site class D and E
Naik *et al.* (2014)	Kanpur	V_s - 125 to 825 m/s
Chakrabortty et al (2018)	Jaipur	Site class C and D
Sairam *et al.* (2018)	Ahmedabad	V_s - 260 to 360 m/s Site class D
Parhi *et al.* (2020)	Korba, Vijaywada	V_s - 149 to 245 m/s Site class D
Singh *et al.* (2021)	Varanasi	V_s - 310 to 690 m/s Site class C and D
Imam *et al.* (2022)	Jamshedpur	V_s - 402 m/s Site class C
Aas and Sinha (2023)	Himalayan foothills	V_s - 285 to 375 m/s Site class C and D

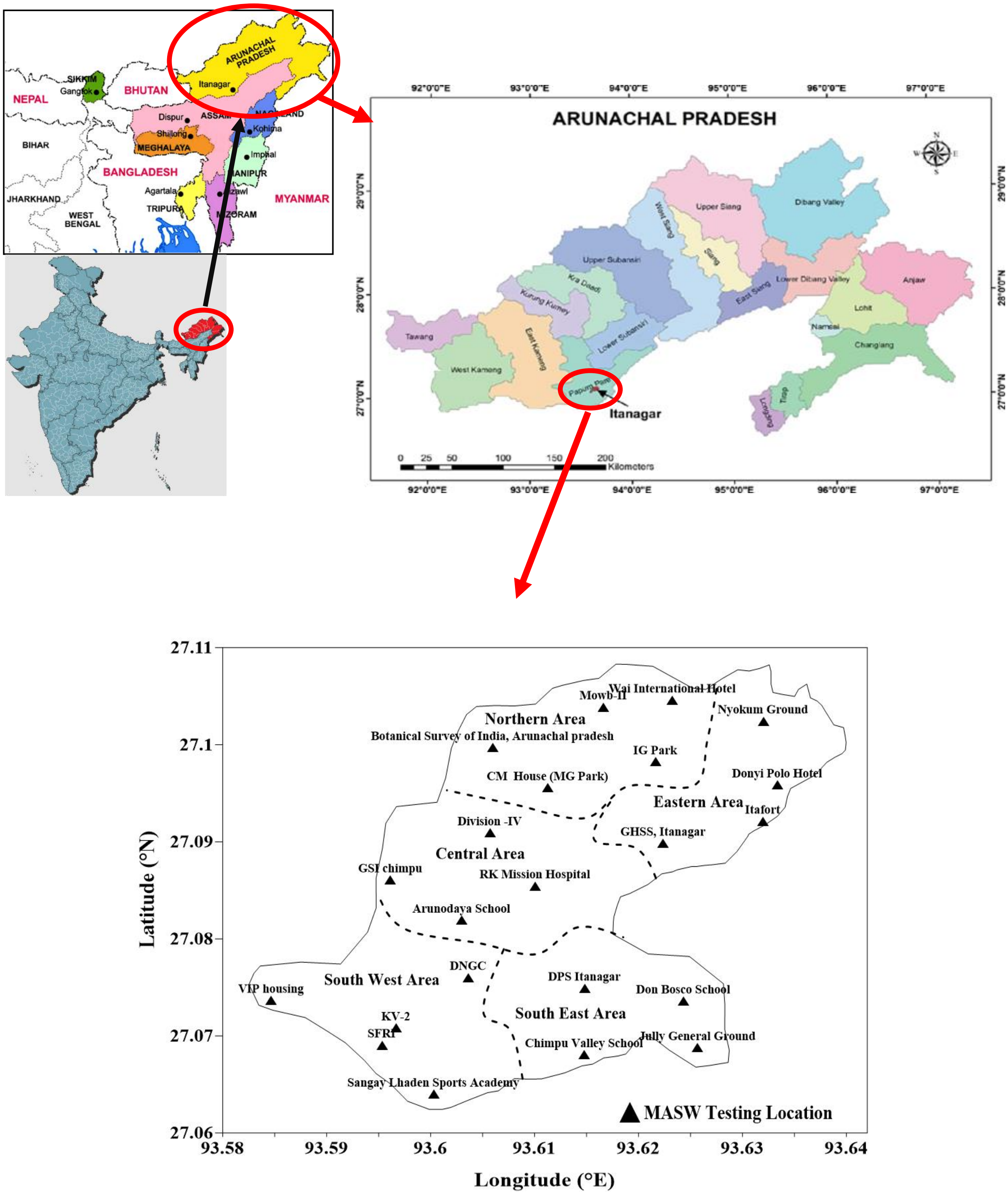


Fig. 1 Study area with MASW testing Locations in Itanagar region

Table 3 Study area and its demarcated divisions

Division	Area	Name of testing location
1	Northern Area	Botanical Survey of India (BSI), Chief Minister House (CMH), Indira Gandhi Park (IGP), Mowb-II, Wai International Hotel (WIH)
2	North Eastern Area	Nyokum Ground (NG), Donyi Polo Hotel (DPH), Itafort (IF), Government Higher secondary school (GHSS)
3	Central Area	Geological Survey of India (GSI), Arunodaya school (AS), Rama Krishna Mission (RKM), Division-IV (Div-4)
4	South West Area	Dera Natung Government college (DNGC), Kendriya Vidyalaya-II (KV2), VIP Housing, Sangey Lhaden Sports Academy (SLSA), State Forest Research Institute (SFRI)
5	South East Area	Chimpu Valley school (CVS), Don Bosco School (DBS), Delhi Public School (DPS), Jully General Ground (JGG)

All the testing locations were selected in such a way that it approximately covers the entire Itanagar region. For the present study, all testing site location of Itanagar city is divided into 5 divisions as shown in Table 3. According to the soil data available for all the locations, it can be stated that most of the locations, as listed in Table 3, consists of light brownish to tan colored silty sand up to a very shallow depth (up to 1.0 m from surface level) followed by thick layer of fine grain sand or poorly graded sand. Based on the borelog profile reported by Anshu *et al.* (2024), similar soil deposits were observed for Itanagar region.

4. Seismicity and Seismo-tectonic feature of the Study Area

From the past seismic scenario, it is noticed that the study area has experienced several earthquakes of low to high magnitudes (Fig. 2), due to the release of huge amount of strain energy. This is primarily attributed to the continuous dipping down of the Indian plate under the Eurasian plate by the displacement rate of 50 mm/year (Roy and Purohit 2018). Owing to the seismicity as well as the existence of complex structure of faults and the fractures, the study area becomes substantially prone to earthquakes (Nandy 2001; Kumar *et al.* 2007). As per seismotectonic atlas published by Geological Survey of India (SEISAT, 2000), there are different tectonic features such as lineament, shear zone, fault and thrust being present within 500 km radial distance of Itanagar, as shown in Fig. 2. As a result, the region has witnessed several earthquakes of different magnitudes such as the 1950 Great Assam earthquake (8.6 M_w), Shillong earthquake of 1897 (8.7 M_w), and Cachar earthquake of 1869 (8.6 M_w). Based on the prevalent seismicity and tectonic features of North East India, Itanagar belongs to the most active tectonic regions in the world (Kayal 1998). IS:1893 (2016) has also placed the Itanagar region in seismic zone V with a zone factor of 0.36g. Evans (1964) has reported that the Shillong hills massif, which is an intra plate tectonic domain and that witnessed the 1897 Great Shillong earthquake (8.7 M_w), is located within a distance of about 170 km south west of Itanagar. The southern part of the Shillong massif is demarcated by the Dauki Fault has records of earthquake events having magnitude as high as 7.0 M_w. Towards the eastern part, the Shillong massif is separated from the Mikir Hills massif by the Kopili Fault. Moreover, the seismic source zone, located south of Itanagar at about 65 km, hosts a number shallow focus earthquakes mainly concentrated along Kopili Fault with a highest recorded magnitude 7.2 M_w.

The major tectonic features falling in this zone are Main frontal thrust (MFT), Main boundary thrust (MBT) and Himalayan fold thrust (HFT). The Itanagar urban agglomeration situated within this source zone is bounded by HFT in the south and MBT in the north. The majority of the earthquakes originating from this zone are shallow focus earthquakes with the highest instrumented earthquake magnitude being from the Main central thrust (MCT). The N-S trending Tripura-Mizoram thrust fold belt hosts the 1984 Cachar earthquake of M_w 6.0. Further, Mishmi tectonic Block, located at about 250 km east of Itanagar, comprises NW-SE trending Lohit Thrust, Tidding suture and the Mishmi Thrust. Numbers of shallow focus earthquakes as well as the largest earthquake such as 1950 Assam earthquake of M_w 8.6 was generated from this source zone. Furthermore, the Indo-Burma subduction zone lies within the south-southeast of Itanagar at a distance of about 150-180 km. This seismogenic zone extends throughout the eastern boundary of the country covering the Border States like Mizoram and Manipur in the south and Nagaland in the north, where it terminates along the Mishmi block. Since the entire Itanagar region is associated with largest active seismotectonic domain, it comes under seismic Zone-V (IS-1893, 2016). Further, based on the sediment deposit, lithology and nature of occurrences, Singh (2007) has classified the quaternary sediments into Itanagar Formation, Bandardewa Formation, Sonajuli Formation and Pachin Formation. Further, Siwalik sediments classify as Bomdila thrust, Kimin formation, Subansiri formation and Dafla formation. Itanagar is situated on the Siwalik sediments and quaternary deposits with a number of active faults, lineaments and some prominent thrusts (Singh, 2007). The quaternary sediments consist of poorly sorted boulders, pebbles, gravels, mud, sand and clay. Given the heterogeneous nature of the subsurface deposits and their varying mechanical properties, it is essential to accurately determine the shear wave velocity (SWV) profiles across different depths. The Multichannel Analysis of Surface Waves (MASW) technique offers a robust and non-invasive method for evaluating the subsurface shear wave velocity distribution, providing crucial insights into the stiffness and dynamic properties of these geological layers. The following section describes the methodology employed in this study, focusing on the application of MASW to characterize the shear wave velocities in the study area.

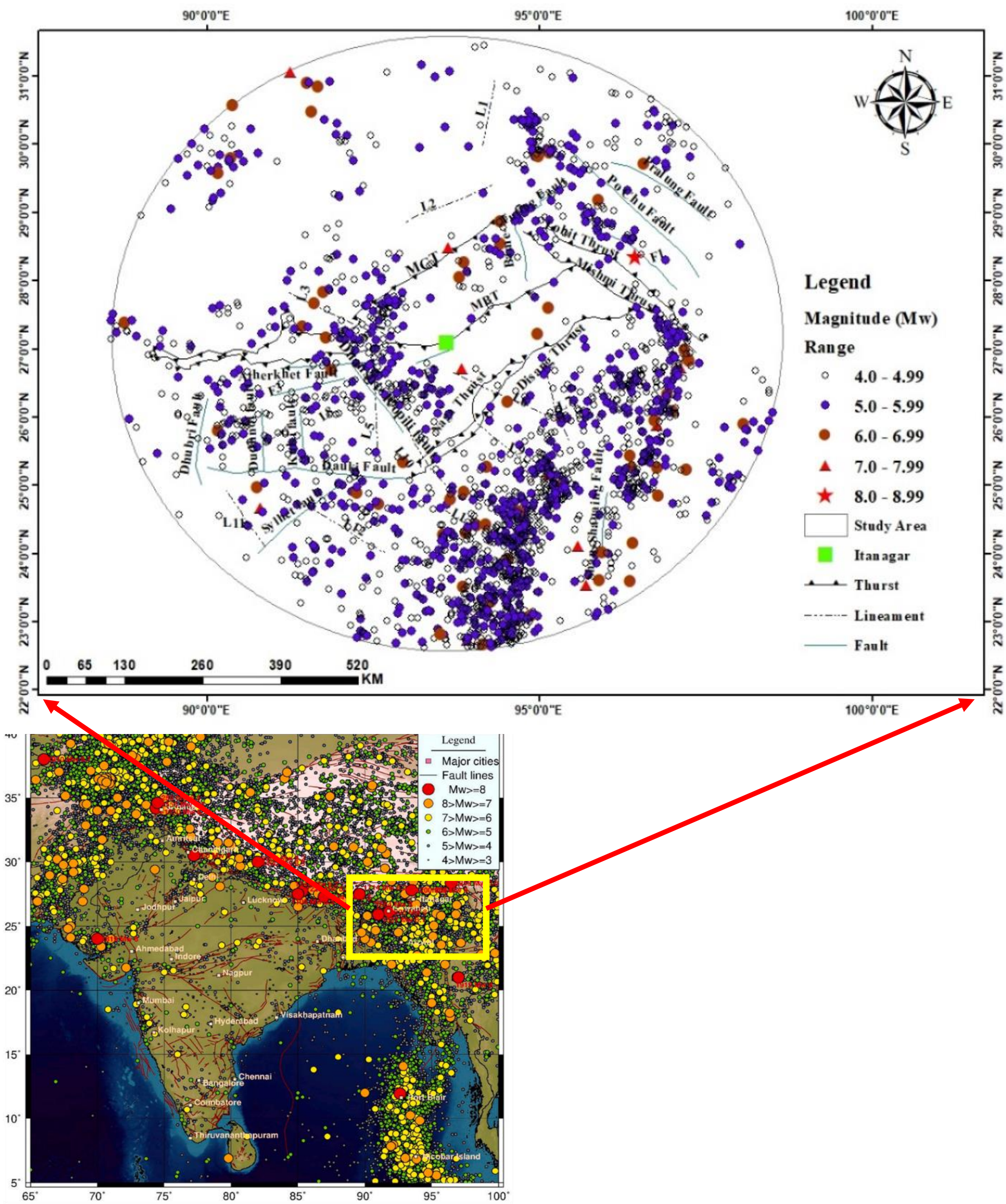


Fig. 2 Seismicity and seismotectonic features of study area

5. Multichannel Analysis Surface Wave (MASW) Survey

In the present study, active MASW survey has been carried out, at different locations of Itanagar, to assess the seismic site characterization based on subsurface SWV. The catastrophic damage due to seismic activity, either in terms of ground failure or in terms of structural failure, is majorly associated with site-specific soil properties from the surface level to bed rock. Therefore, the characterization of site-specific soil properties is of utmost importance for the site-classification as well as for the design of seismically resilient structures. Site classification, which indicates the importance of local site effect on the seismic waves along with the surface geology and seismological data, is also a pertinent starting point utilized for seismic microzonation. To characterize the study area in terms of the variations of SWV along the depth, as well as to observe its significance on the seismic wave amplification, a framework is followed, as shown in Fig. 3. Initially, the locations of study area are identified where MASW is conducted to collect the field data. Thereafter, the analysis and interpretation of the collected data is carried out using Surfseis software considering the NEHRP guidelines.

MASW is a non-invasive geophysical technique used to assess the subsurface characterization of soils and rocks (Park *et al.* 1999;). As part of an active MASW survey, there are typically three stages, data acquisition, dispersion analysis, and inversion analysis, each of which depends on the previous stage (Taipodia *et al.* 2021). The details of the active MASW survey can be found to be listed in various available literature (Zhang *et al*. 2004; Xia *et al*. 1999; Dikmen *et al*. 2010; Park 2011; Taipodia and Dey 2018; Taipodia *et al.* 2019, 2020b). In the present study, the acquisition of field data at all 22 locations was carried out using active MASW survey (as shown in Fig. 1). The majority of survey sites chosen are situated on level terrain in significant locations such as parks, hospitals, schools, and temple grounds. The key field parameters, including the distance between the source and the first and last receiver, receiver spacing, and the length of survey lines, were carefully determined to ensure that the necessary depth of information could be effectively acquired. Further, based on the collected data, the SWV profiles were obtained for all 22 locations of Itanagar region of Arunachal Pradesh (India).

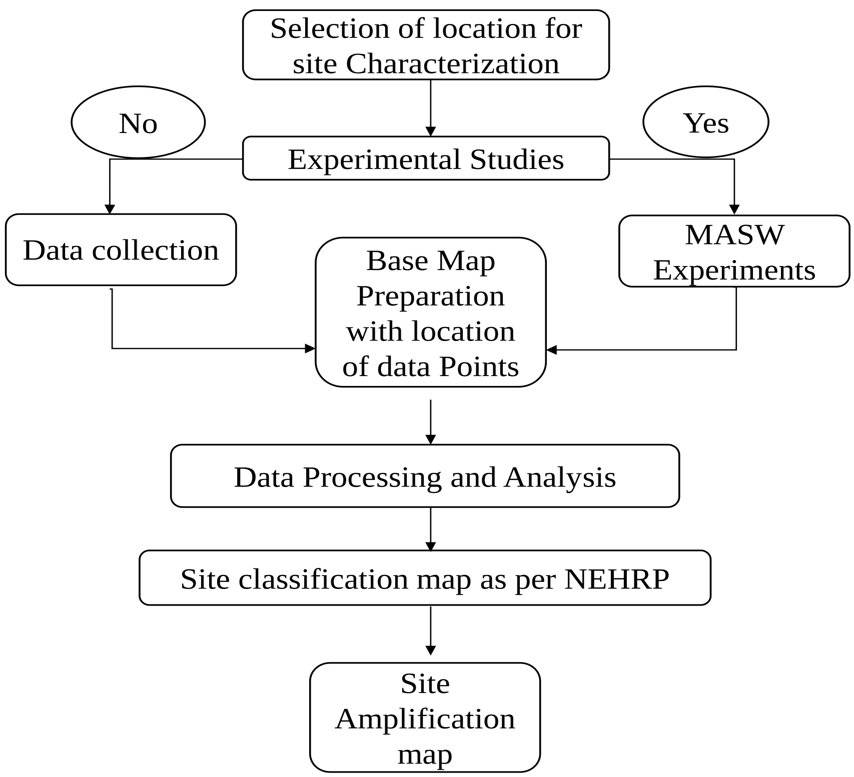


Fig. 3 Flowchart outlining the general methodology for seismic site characterization and amplification mapping.

As per the recommendations provided by Taipodia *et al.* (2017), the tests were performed using 24 numbers of geophones having frequency 4.5 Hz. Geophones were attached firmly on the ground surface in the series following a straight line, at a spacing of 1.0 m, and interconnected with a cable that is connected to a Geode seismograph for recording the shots gathered. A sledgehammer of 10 kg was connected with a geode seismograph through a hammer cable to record the initial time while hitting at the 300×300 mm size mild steel plate to generate surface waves. This test is repeated thrice after considering 2.0 m, 3.0 m and 4.0 m offset from the first geophone placed near the source to avoid near field effects. For each of the data acquisition exercise, the sampling time and frequency have been considered as 0.8 s and 4000 Hz, respectively. Five shots are applied one after another consecutively, to generate a stacked shot gather file to avoid the uncertainty/error involved with the actual energy delivered in the test sample (Taipodia *et al*., 2020a). These waves are sensed by the geophones and are stored as a field file of shot gathers.

6. Results and Discussion

6.1 Shear wave velocity profiling and seismic site classification based on V_{s30}

Figure 4 illustrates the raw wavefield collected at the field by the seismograph. This field data is further analyzed using Surfseis software (version 6.0) to get SWV profiles with depth. As a part of the pre-processing of the collected wavefields, following the proposition of Taipodia *et al.* (2018a), the noisy region in the time-domain record is muted and filtered out (with the aid of a bandpass filter in a range of 5-180 Hz or likewise as governed by the amplitude spectra of individual site records) as their presence often lead to inaccurate results in the subsurface shear-wave velocity profiles due to the contamination of recorded signals. Such noises can largely originate due to the presence of adjacent structures or intervening foundations. Therefore, in order to avoid any such inherent noise in the present study, the test locations were mostly chosen in the plain areas such as school grounds, college quads or open space that are quite far away or free from heavy traffic as well as heavy industrial area. Such precautions aid to obtain dispersion images with a higher signal-to-noise ratio (SNR), which is the key to extract the best suited dispersion curve from the phase velocity-frequency space either through a manual or an automated procedure (Taipodia *et al.* 2020a, 2020b). Figure 5(a-d) presents the dispersion image and the corresponding fundamental mode dispersion curves obtained for the four typical sites i.e. the (a) DPS (b) GHSS (c) IG park (d) Botanical Survey of India (BSI).

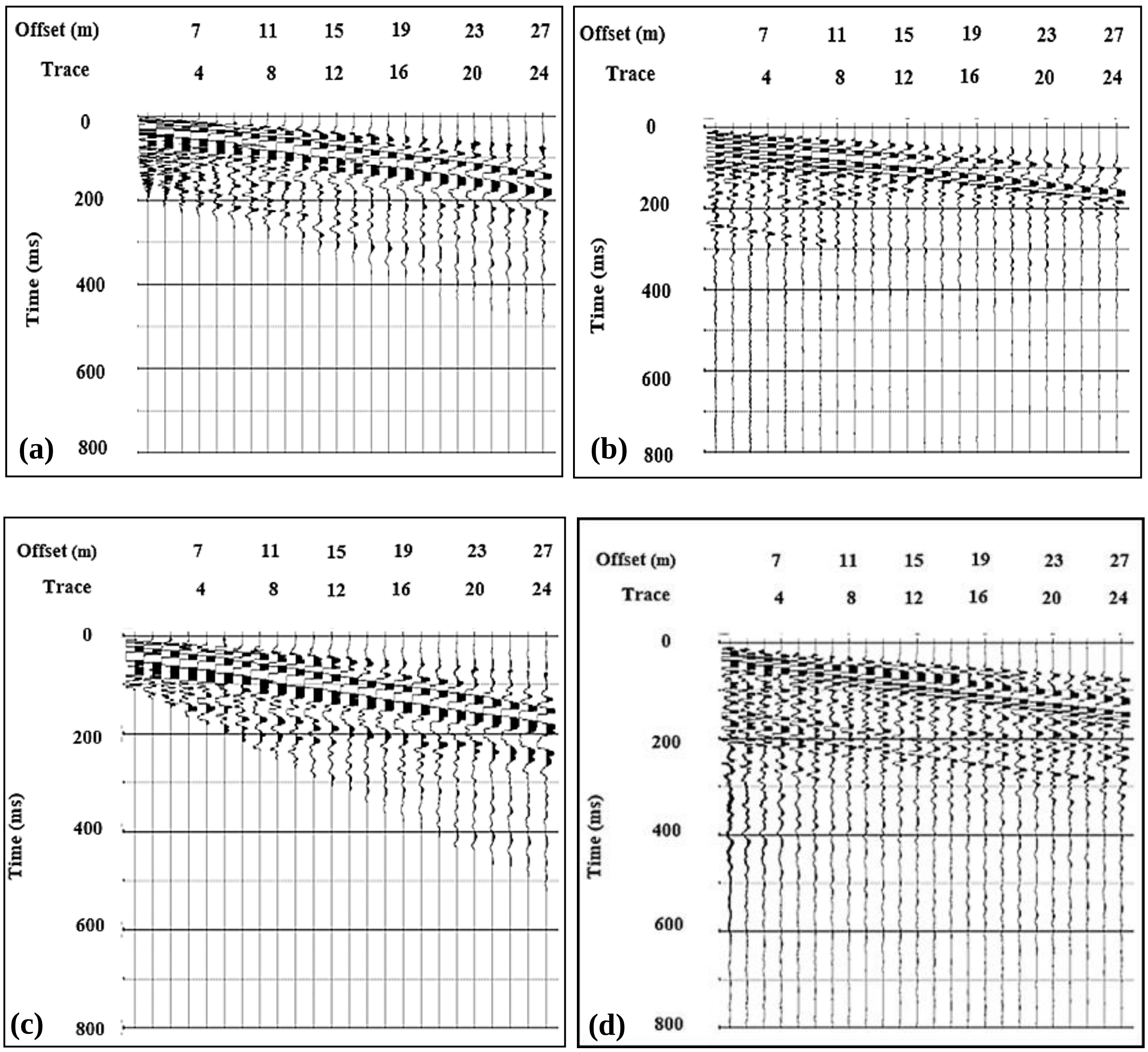


Fig. 4 Wavefield records obtained from MASW survey conducted at (a) DPS (b) GHSS (c) IG park (d) Botanical Survey of India (BSI)

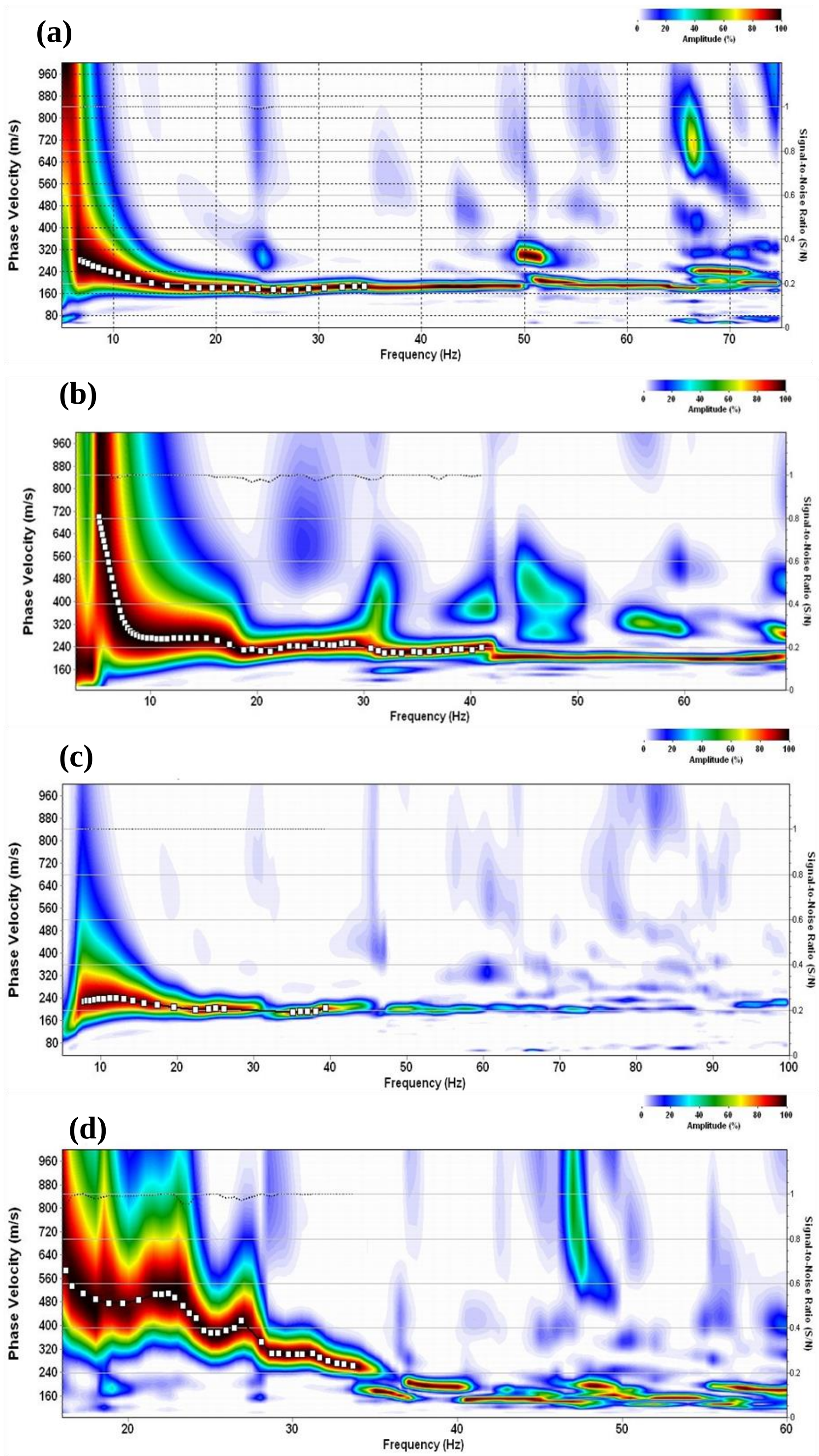
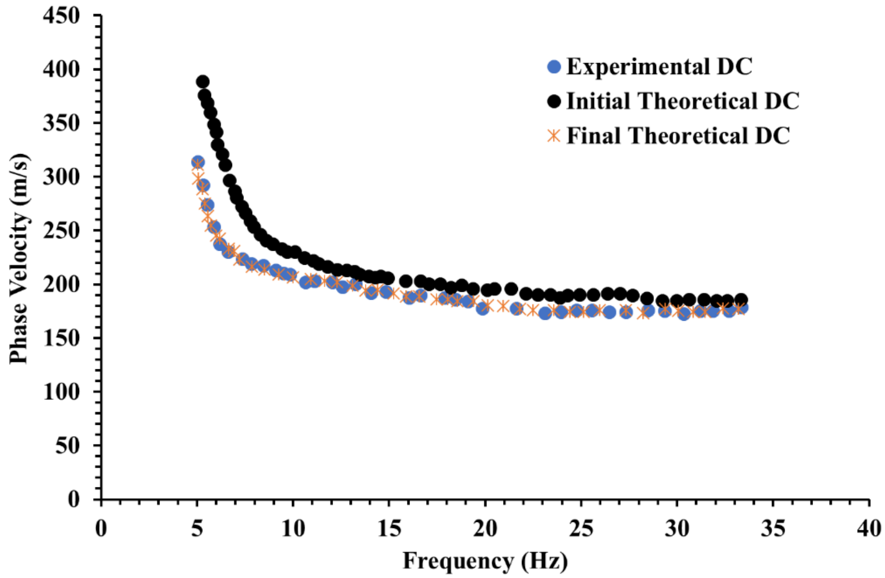


Fig. 5 Dispersion image obtained from MASW survey conducted at (a) DPS (b) GHSS (c) IG park (d) Botanical Survey of India (BSI)

Further, the extracted dispersion curve is utilized in an iterative inversion process to estimate the SWV profile at each of the sites. Based on an initially chosen layered earth model (as per the recommendations of Xia *et al*. 1999 and Taipodia *et al*. 2018b), the theoretical dispersion curve is generated and the same is compared to the extracted experimental dispersion curve at the end of each iteration. Based on the disparity between the theoretical and experimental dispersion curve at the end of each iteration, the layered earth model is updated i.e. the parameters defining the earth model such as the Poisson's ratio, density and shear wave velocity of each layer are improvised, while maintaining the thickness of each layer to be unchanged. The process is repeated until the disparity between the experimental and theoretical curve reduces below the tolerance level in the root mean square error (RMSE ≤ 10) (as per Baglari *et al.* 2020). For each of the sites (IG, GHSS, BSI and DPS), Figure 6 exhibits the experimental dispersion curve (as obtained from Fig. 5), initial dispersion curve that is used to commence the inversion analysis and the final dispersion curve obtained at the end of the inversion process. For the referred sites (IG, GHSS, BSI and DPS), the RMS error has been found to be 4.59, 3.26, 4.76 and 3.49, respectively, that are well within the tolerance limit. The one-dimensional SWV profile obtained from the last iteration is considered as the final one for the site of experimentation. Figure 7 shows the consequent shear wave velocity profile obtained as an outcome of the inversion process for the DPS, GHSS, IG Park and Botanical Survey of India (BSI) survey locations.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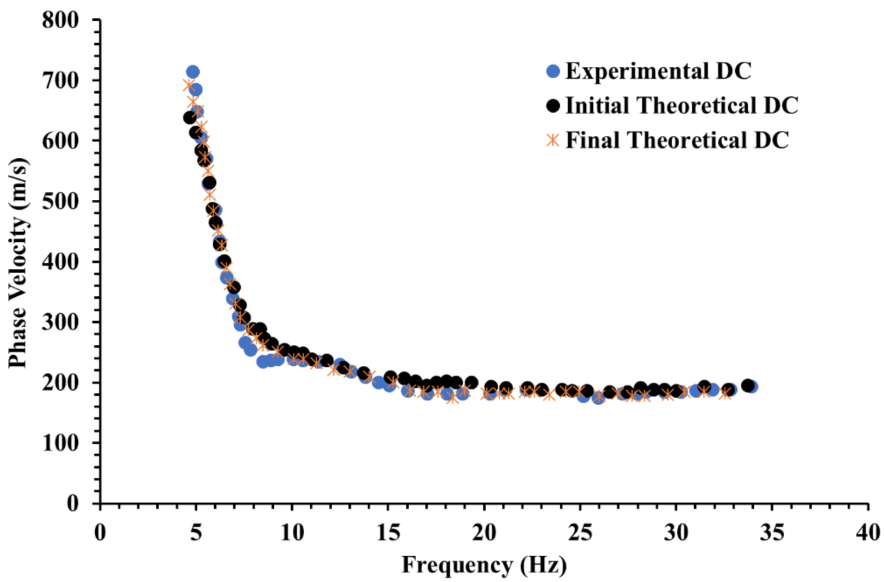
(a)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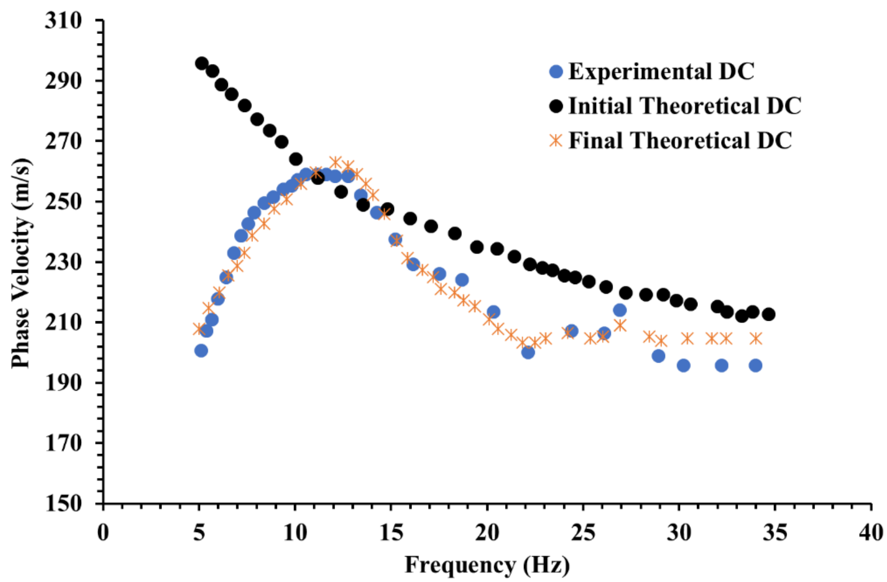

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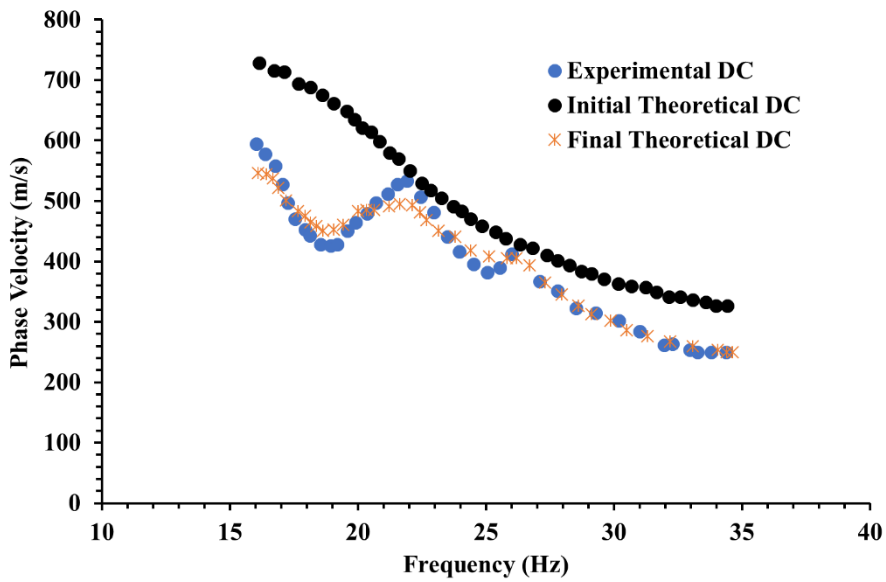


(d)

Fig. 6 Comparative evaluation of the initial and final dispersion curves obtained from inversion process in terms of the experimental dispersion curve obtained from field data at (a) DPS (b) GHSS (c) IG park (d) Botanical Survey of India (BSI)

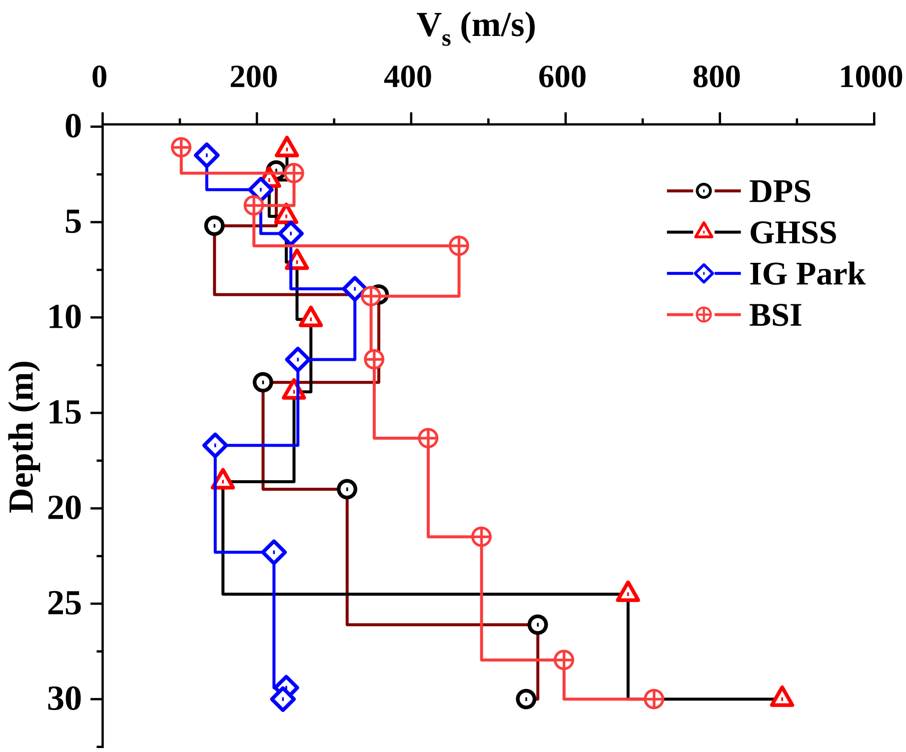


Fig. 7 Shear wave velocity profile obtained from active MASW survey conducted at (a) DPS (b) GHSS (c) IG park (d) Botanical Survey of India (BSI)

In a similar process, after performing dispersion and inversion analysis on the field data collected from rest of the 22 locations, SWV profiles were generated for all the chosen location in the Itanagar City. Figure 8(a-e) shows the obtained SWV profiles with the test locations segregated into different zones that were demarcated for the Itanagar region (shown in Fig. 1, and listed in Table 3). Overall, it shows that the minimum SWV is nearly 102 m/s whereas, maximum SWV is found to be 1294 m/s. It can also be well observed that the SWV profiles along the depth does not follow a particular trend, rather fluctuations are noted in the SWVs with the increasing depth. This indicates that the soils in the Itanagar region is heavily layered and heterogeneous comprising stratifications of softer and stiffer soils, that corroborates to the depositional geology of the area. An increase in SWV with depth indicates the presence of a relatively stiffer medium in comparison to the overlying medium, and vice-versa. It can be noticed from all the soil profiles that, with some exceptions, the soil layers within a depth of 10 m are relatively softer than the layers at the underlying depths, i.e. at 10-30 m. Figure 9 presents a contour map illustrating the spatial distribution of average shear wave velocity for the top 30 meters (V_{s30}) within the Itanagar region. This map visually represents variations in subsurface stiffness, with color gradations indicating V_{s30} values ranging from approximately 200 m/s (soft soils, shown in blue shades) to over 600 m/s (stiff soils or rock, represented by red shades).

The National Earthquake Hazard Reduction Program (NEHRP 2020) as well as International Building Code (IBC 2023) have recommended the usage of average SWV until 30 m depth from the ground level (i.e., V_{s30}) for site classification purpose. This adaptation is attributed primarily on the understanding that the shear wave velocity in the top 30 m soil profile mostly influences the ground response under seismic conditions. Hence, based on the guidelines provided by NEHRP (2020) and the obtained SWV profiles, for all the 22 locations mentioned in Table 3, the site classification is conducted for the Itanagar region of Arunachal Pradesh, India. V_{s30} for all 22 sites are estimated using Eqn. (2), and the same is presented in Table 4. Comparing the V_{s30} obtained at the 22 sites as per NEHRP guidelines given in Table 4, it is noticed that all the sites fall in the site classes C to DE. Figure 8(a-e) also shows that with some exceptions, the soil within the depth of 10 m has a SWV lesser than 800 m/s, thereby indicating presence of softer or medium dense soils (as per Table 1) that are supposedly more responsible for the amplification of seismic waves. Further deeper, moving towards 30 m from the ground surface, the SWV increases up to 1200 m/s thereby indicating the existence of stiffer soil at larger depth (as per Table 1).

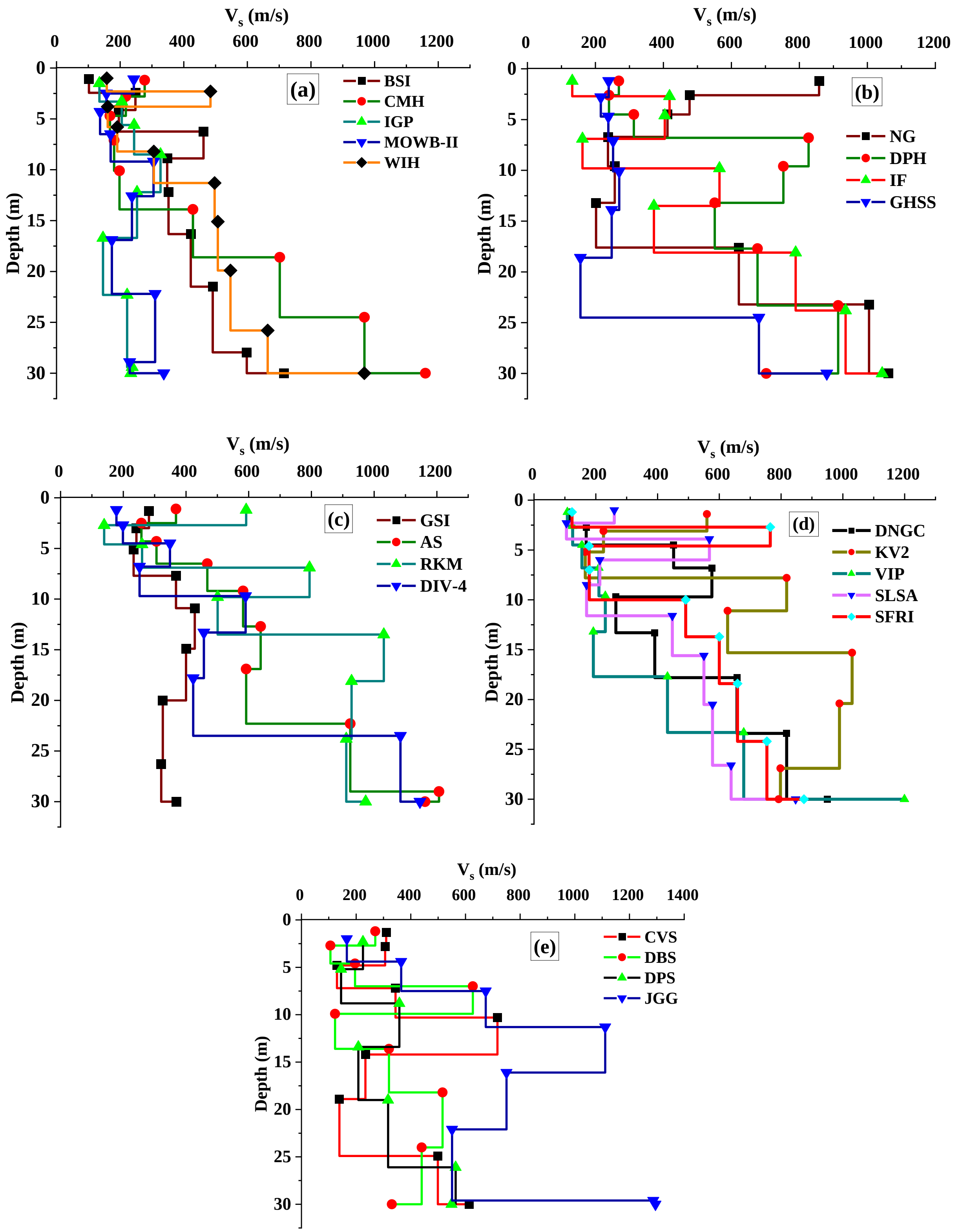


Fig. 8 SWV profile for all test locations (a) Northern area (b) North-eastern area (c) Central area (d) South-west area (e) South- east area of Itanagar

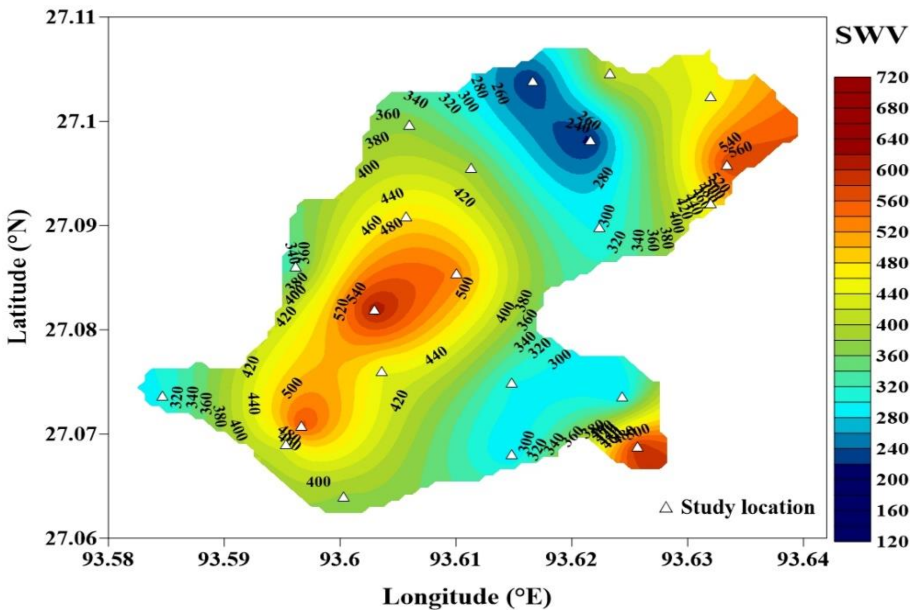


Fig. 9 Contour map depicting spatial distribution of average shear wave velocity (V_{s30}) in Itanagar region classified as per NEHRP (2020), with triangular markers indicating MASW survey locations.

6.2 Estimation and spatial mapping of seismic wave amplification

In general, on account of lessening of confining stresses, seismic wave amplification occurs as the horizontal shear waves mover through the propagating media to the ground surface. Depending upon the stiffness and damping characteristics of the layered media, attenuations can also occur locally in some specific layers. Depending on the extent of amplification of seismic waves, supporting structures may suffer minimal to severe damage. Therefore, it is utmost important to characterize and identify the degree of amplification of seismic waves, especially in a seismic prone area. In general, amplification factor (AF) is most pertinently used to characterize amplification and is defined as the ratio of the peak ground acceleration to the peak acceleration of the input motion. For the present study, two approaches are used to assess the amplification factor, namely using the empirical approach proposed by Midorikawa (1987) approach.

To estimate the amplification factor, an empirical equation proposed by Midorikawa (1987) is used in this study. Based on V_{s30}, the amplification factor at the ground surface is expressed as:

$$\begin{aligned} AF &= 68 \times V_{s30}^{-0.6} \quad \forall V_{S30} < 1100 \ m/s \\ &= 1 \quad \forall V_{S30} \geq 1100 \ m/s \end{aligned} \tag{3}$$

Based on Eqn. (3) and V_{s30} values obtained for all 22 test sites in the Itanagar region, the AF is estimated and the same is tabulated in Table 4. It can be seen from Table 4 that V_{s30} of all the 22 sites are less than 1100 m/s. Accordingly, the amplification factor is found to be in the range of 1.43 to 2.73. The spatial distribution of ground level amplification factor over the Itanagar region is presented as a contour map as shown in Fig. 10. It is observed that the soil sites with predominantly softer or relatively less stiff soils reflect high amplification value. Most of the area of Itanagar region reflects high amplification of seismic waves, and the same should be invariably taken into account in the design seismically resilient structures or assessing the health of the existing structures in the region to avert damage due to amplification in the soft soil.

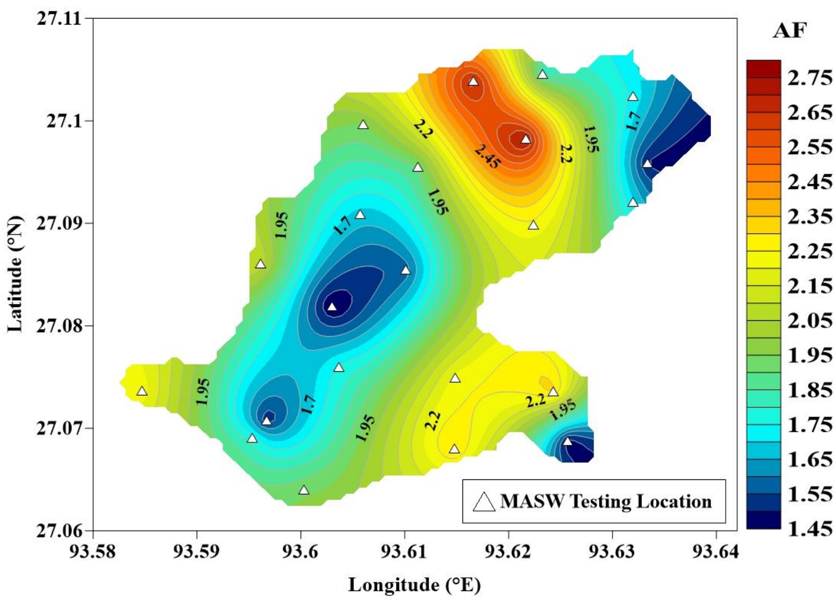


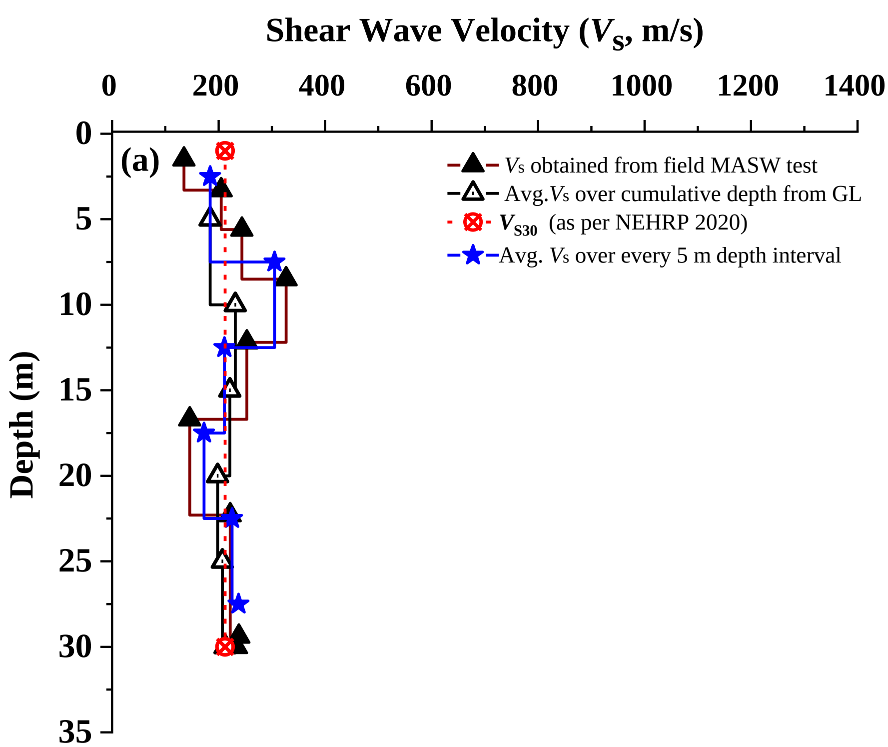
Fig. 10 Contour map of amplification factor in the Itanagar region based on Midorikawa's (1987) empirical approach

Table 4 Summary of Site classification of 22 test locations as per NEHRP (2020) guidelines and wave amplification using empirical equation by Midorikawa (1987)

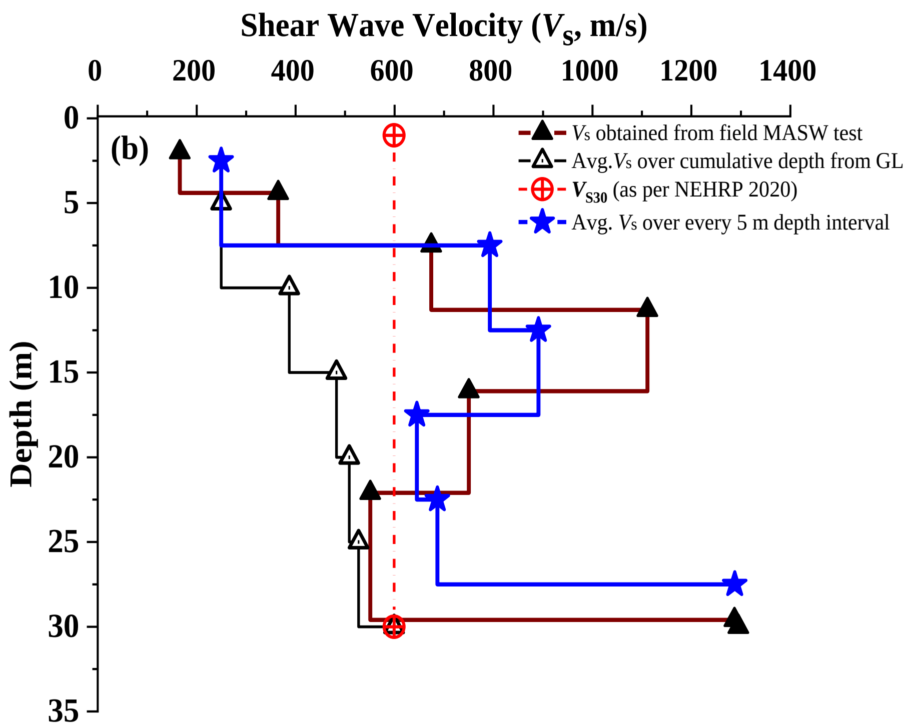
Zone	SN	Longitude	Latitude	Name	Average V_{s30}	Site Class as per NEHRP (2020)	AF (Midorikawa 1987)
Northern area	1	93.606	27.09969	Botanical Survey of India (BSI)	373.03	CD	1.95
	2	93.6113	27.09555	CM House(CMH)	385.69	CD	1.91
	3	93.6216	27.09823	IG Park (IGP)	212.38	DE	2.73
	4	93.6166	27.10388	MOWB-II	219.1	DE	2.68
	5	93.6233	27.10458	Wai International Hotel (WIH)	414.48	CD	1.83
North-east area	6	93.632	27.10243	Nyokum Ground (NG)	451.9	CD	1.74
	7	93.6334	27.09585	Donyi polo hotel c-Sector (DPH)	580.17	C	1.49
	8	93.632	27.09211	Itafort (IF)	464.97	CD	1.71
	9	93.6224	27.08983	GHSS	295.84	D	2.24
Central area	10	93.5961	27.08607	GSI Chimpu	331.61	CD	2.09
	11	93.603	27.08191	Arunodaya School (AS)	618.89	C	1.44
	12	93.6101	27.08545	RK Mission Hospital (RKM)	535.13	C	1.57
	13	93.6057	27.0909	Division -4 (DIV-4)	476.77	CD	1.68
South-west area	14	93.6036	27.07601	DNGC	441.2	CD	1.76
	15	93.5967	27.0708	KV 2	572.08	C	1.51
	16	93.5847	27.07365	VIP Housing	298.08	D	2.23
	17	93.6003	27.06398	Sangay Lhaden Sports Academy (SLSA)	375.69	CD	1.94
	18	93.5953	27.06904	SFRI	431.43	CD	1.78
South- east area	19	93.6148	27.06804	Chimpu Valley School (CVS)	281.45	D	2.31
	20	93.6243	27.07358	Don Bosco School (DBS)	279.1	D	2.32
	21	93.6148	27.07491	DPS Itanagar	300.75	D	2.22
	22	93.6257	27.06877	Jully General Ground (JGG)	599.17	C	1.47

6.3 Enhanced subsurface characterization through interval-averaged SWV mapping

Figure 11 reflects an interesting observation in regard to the pitfall of using NEHRP classification system by using the V_{s30} as the primary quantifier. In this regard, two specific sites are chosen, IGP and JGG, in which the latter one exhibits significant fluctuation in the shear wave velocity profile with depth thereby indicating substantial layered heterogeneity while the former exhibits a SWV profile with magnitudes mostly in close range over the depth, thereby indicating a nearly homogeneous medium. It can be observed from Table 4 that IGP is classified as site class DE with V_{s30} = 212.38 m/s, while JGG is classified as site class C with V_{s30} = 599.17 m/s. The same is plotted in Fig. 11 with the aid of red dotted lines. It can be well understood that although for IGP site, the assessment of V_{s30} closely pertains to the SWV profile (Fig. 11a), the same is exorbitantly different for the JGG site. For the JGG site, a significant underestimation or overestimation is noted in comparison to the actual SWV obtained from MASW at different depths (as shown in Fig. 11b). For the JGG site, the soil within the depth of 7.5 m and from 12.5 m to 17.5 m is relatively softer in nature with SWV < 400 m/s as obtained from MASW survey. However, if the V_{s30} is considered, the same soil reflects much stiffer behavior. Hence, this observation clearly reflects that the consideration of V_{s30} is not an acceptable way of demarcating site classes for those sites exhibiting remarkable layered heterogeneity. In such cases, if V_{s30} is used as per the NEHRP classification for the seismic design of structures, due to unrealistic assumptions of ground conditions, the seismic design parameters might be completely erroneous. Thus, adapting V_{s30}–based site classification should be avoided for such sites, and using the actual SVW profile for further seismic analysis is always recommended. However, on the other hand, if the SWV profile comprises approximately close magnitudes along the depth, then the consideration of V_{s30} can be well acceptable for such homogeneous or nearly homogeneous ground conditions, as can be seen in the Fig. 11a for the IGP site. Thus, in a nutshell, it can be stated that if the actual SWV obtained from MASW test is available for a site, the adaptation of V_{s30} as per NEHRP classification should be preferably avoided for the seismic design of structures as it might deviate from the realistic ground scenario. Dutta *et al.* (2000) have also reported that the NEHRP site classification may not widely applicable due to significant heterogeneity of soil, local variability and limited geotechnical data, which actually hinders the practical application of V_{s30} in some context. From the present study, it is understandable that V_{s30}-based site classification provided by NEHRP (2020) is suitable only for nearly homogeneous soils wherein the shear wave velocity with depth does not vary significantly. For layered media with significant variability in the soil stiffness with depth, it is not reliable to consider the V_{s30}-based site classification and should be avoided.



(a)



(b)

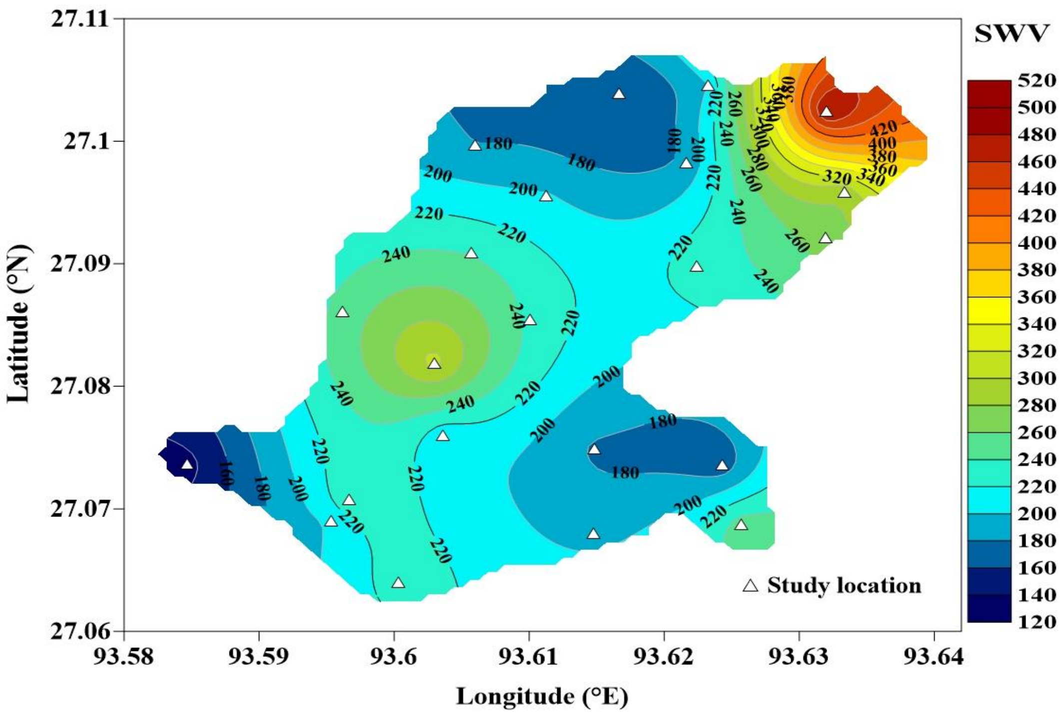
Fig. 11 Plot for SWV from MASW, average SWV from GL, and V_{s30} for two typical locations (a) IGP and (b) JGG

Hence, in this regard, following the standard way of representing average SWVs at any depth from the ground surface as per Eqn. (1), an attempt is made to devise a more scientific way to represent the variation of SWV along the depth obtained from MASW survey that can be directly used for GRA studies. As an example, the average SWV corresponding to the cumulative depths of 5 m, 10 m, 15 m, 20 m, 25 m and 30 m from GL (i.e. V_{s5}, V_{s10}, V_{s15}, V_{s20}, V_{s25}, V_{s30}) are computed for two typical sites of IGP and JGG, and the same is plotted in Figure 11a and 11b, respectively. Although this technique of representation provides much better picture than the one represented by a single magnitude of V_{s30} for the entire depth of soil, yet the interpretation from this representation technique is not easily comprehensible from the plot. Apart from V_{s5} that contains the information of SWV from the top 5 m from the ground level, each of the estimated average

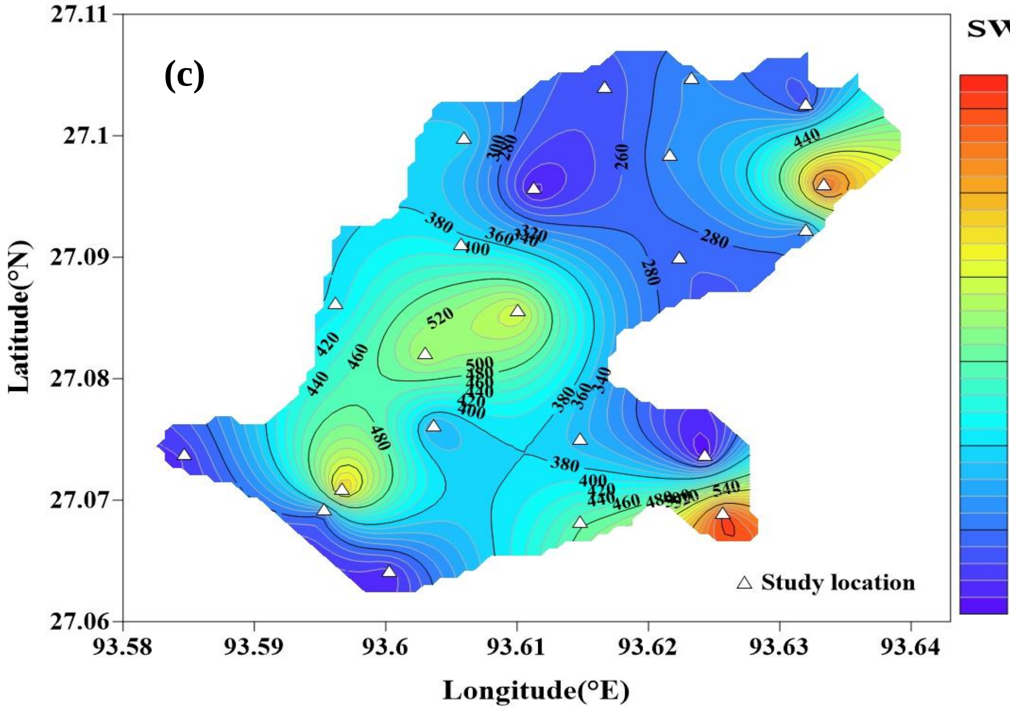
SWV at successive cumulative depths (e.g. V_{s10}, V_{s15} etc.) comprise the information of all the overlying layers, thereby making it very difficult for the reader to distinctly identify the individual influence of successive 5 m depth layers of the soil profile.

Hence, a more cognizant way of representing the variation of average SWV over the depth is required. In this regard, assessment of average SWV at every specific depth interval from the ground surface can offer a more realistic picture of the SWV variation detected from MASW tests. In the present study, the average SWV is found out for the soil layers at every 5 m interval from the ground surface and is represented as $V_{s5(0\text{-}5)}$, $V_{s5(5\text{-}10)}$, …, $V_{s5(25\text{-}30)}$. For each of these successive intervals of 5 m each, the average velocity is represented at a point in the middle of the corresponding layer i.e. in a SWV profile with depth, $V_{s5(0\text{-}5)}$ would be represented at a depth of 2.5 m from the ground surface, and so on for the other intervals. The stated procedure is adopted for the IGP and JGG sites, and the same is exhibited in Fig. 11a and Fig. 11b, respectively. It can be noticed that spatial variation of SWV at the depth interval of 5 m each is a sufficient realistic representation of the actual SWV profile obtained from the MASW survey. The inference drawn is equally applicable both to a nearly homogeneous media (as reflected from the IGP site) and a sufficiently layered heterogeneous media (as reflected from the JGG site). The depth profile of average SWV at every 5 m interval (i.e. $V_{s5(0\text{-}5)}$, $V_{s5(5\text{-}10)}$, …, $V_{s5(25\text{-}30)}$) can be more preferred representation over the profile of average SWV from GL over particular depths (i.e. a profile exhibiting (i.e. V_{s5}, V_{s10}, V_{s15}, V_{s20}, V_{s25}, V_{s30}) or a constant magnitude of V_{s30} for the entire depth (as prescribed in NEHRP guidelines). The stated technique offers a more realistic presentation of soil properties that can provide a better understanding of seismic behavior, risk evaluation for structural design considerations, ground response analysis and liquefaction assessment for any site under seismic motion.

The spatial variations of SWV within the depth of 0-5 m, 5-10 m, 10-15 m, 15-20 m, 20-25 m and 25-30 m for all 22-sites, are presented in form of contour map in Fig. 12(a-f). It can be seen, from Fig. 12a, that SWV within 0-5 m varies from 133 m/s to 486 m/s. The minimum SWV of 133 m/s is found to be at VIP Housing-site whereas the maximum SWV for the region is found to be 486 m/s at Nyokum Ground-site. However, within 5-10 m depth, the spatial variation of the average SWV is found to be in the range of 181.51 m/s to 792.48 m/s (Fig. 12b); where, the minimum SWV of 181.51 m/s is found to be at Don Bosco school-site whereas the maximum SWV of 792.48 m/s is found to be at the Jully general ground-site. Further, Fig. 12c indicates the contour map of the spatial variation of SWV, within 10-15 m depth and, it shows that SWV varies from 73.71 m/s to 1020.69 m/s where, the minimum and maximum SWV is found to be 73.71 m/s and 1020.69 m/s at IG park-site and RKM hospital-site, respectively. Figure 12d presents the contour map of SWV corresponding to the depth of 15-20 m and it can be seen that the spatial variation of SWV is in the range of 149.6 m/s and 994.4 m/s. The minimum value of the average SWV is obtained at Chimpu valley school-site whereas the maximum average SWV is found to be at KV2 site. Furthermore, the spatial variation of SWV, within a depth of 20-25 m, is found to be in the range of 225.24 m/s (at IG Park) to 1088.27 m/s (at Division-IV-site), as shown in Fig. 12e. Figure 11f presents the contour map of spatial variation of SWV within 25-30 m depth wherein the minimum SWV of 237.47 m/s is found to be at IG Park-site while the maximum SWV of 1287 m/s is found at the Jully general ground site. In supplement to what is already discussed for Fig. 11, the observations from Fig. 12 clearly indicate that a subsoil with layered heterogeneity plays a significant role in local site amplifications, and the contributions from different layers should not be oversighted as they can impart a recognizable spatial variation in seismic response at different sites even within the same city. For example, it is noticeable that the demarcated Central and South-West area of Itanagar exhibits relatively stiffer soils all throughout 5-30 m depth. Comparatively, the rest of Itanagar have soils that are relatively less stiff until a depth of 20 m from their corresponding ground surfaces. This observation clearly indicates the regions that are required to be under scrutiny in regard to seismic hazard assessment. Furthermore, depending on the type of foundation availed for a specific infrastructure, the spatial variations in stiffness along with layered heterogeneity in subsurface demands scrutiny over the site-specific soil-foundation interactions studies to assess the influence of seismic motions at different regions in the city.



(a)


(c)
SWV
820
780
740
700
660
620
580
540
500
460
420
380
340
300
260
220
180
△ Study location
Latitude(°N)
27.11
27.1
27.09
27.08
27.07
27.06
93.58
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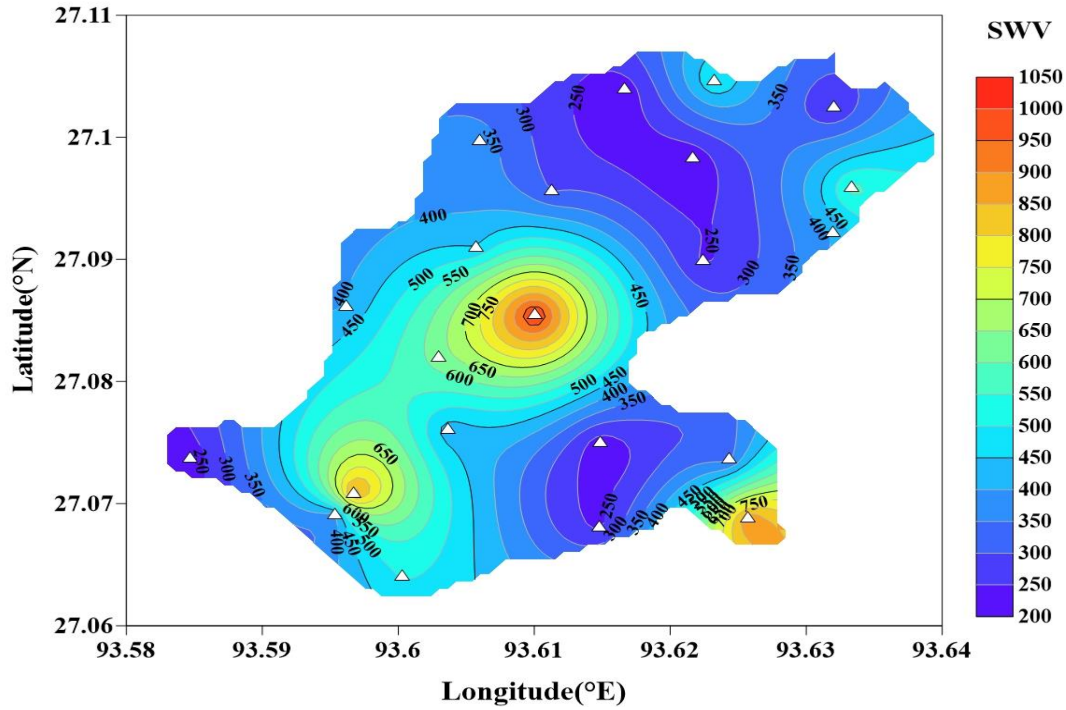
93.6
93.61
93.62
93.63
93.64
Longitude(°E)

(b)


SWV
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Latitude(°N)
27.11
27.1
27.09
27.08
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93.58
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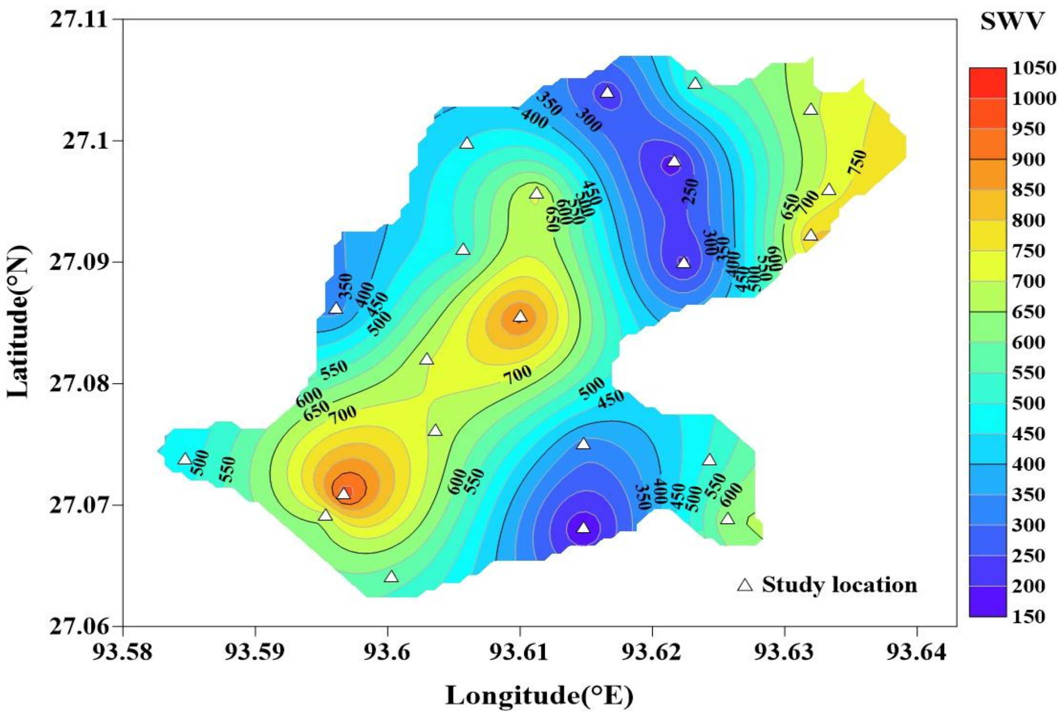
93.64
Longitude(°E)

(c)


SWV
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Latitude(°N)
Longitude(°E)
27.11
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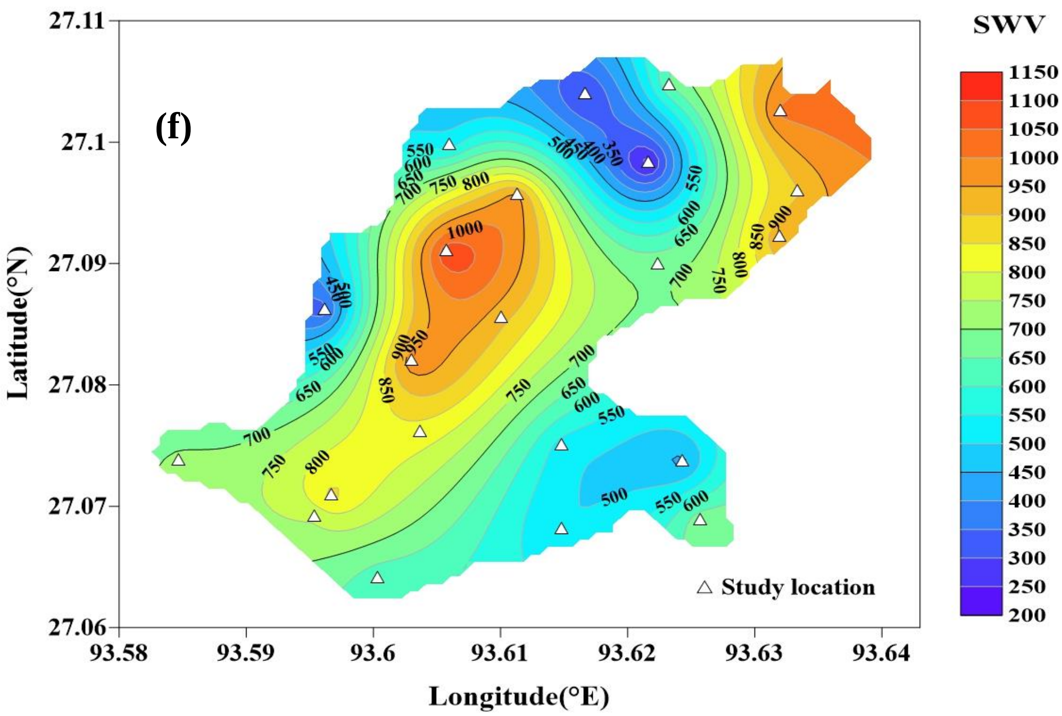
△ Study location

(d)


(f)
SWV
1150
1100
1050
1000
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350
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250
200
Latitude(°N)
Longitude(°E)
27.11
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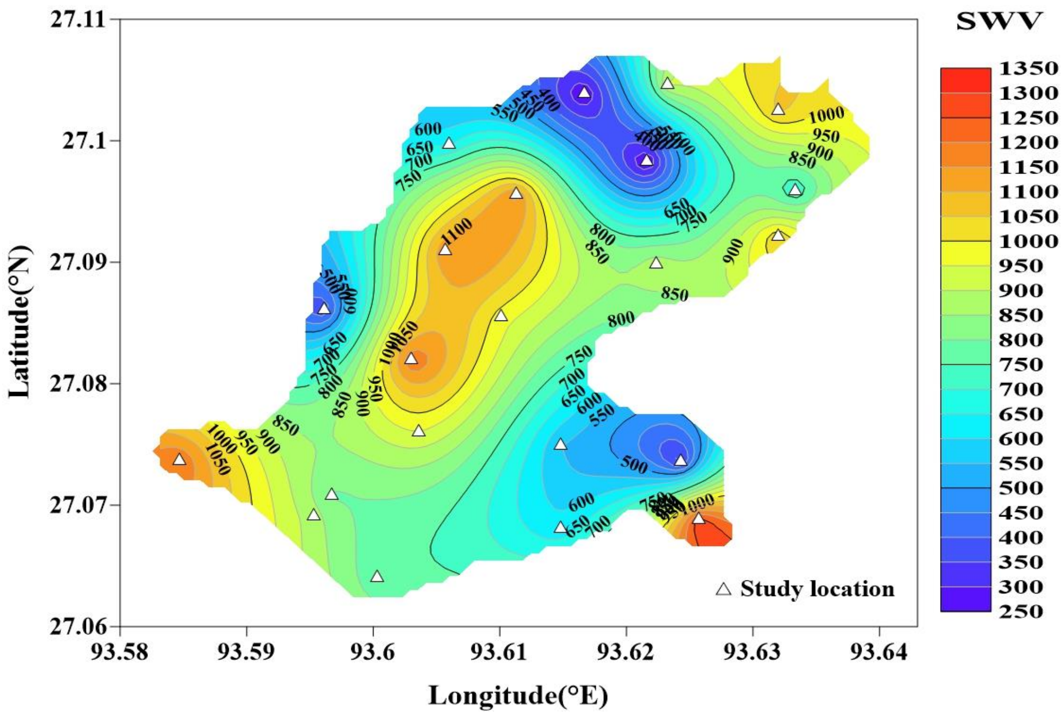
93.63
93.64
△ Study location

(e)



(f)

Fig. 12 Contour map for spatial variation of SWV for Itanagar region represented for (a) $V_{s5(0\text{-}5)}$ (b) $V_{s5(5\text{-}10)}$ (c) $V_{s5(10\text{-}15)}$ (d) $V_{s5(15\text{-}20)}$ (e) $V_{s5(20\text{-}25)}$ and (f) $V_{s5(25\text{-}30)}$

7. Conclusions

Shear wave velocity (SWV) of the subsurface is a primary indicator of stiffness of layered media and is one of the significant contributor to the GRA studies. In the present study, the shear wave velocity profile is determined at 22 locations in the Itanagar region of Arunachal Pradesh (India) using Active Multichannel Analysis of Surface Wave (MASW) survey. Based on the estimated SWV, site classification is carried out as per NEHRP (2020) guidelines of the Itanagar region is conducted. Based on the outcomes and observation, the following conclusions are drawn from the present study:

- As per the seismic site-classification guidelines by NEHRP (2020) and based on the assessed V_{s30} (ranging from 210 m/s to 620 m/s) various locations in the Itanagar city belongs to the site classes C and DE. Accordingly the subsurface of entire city can be considered to be comprising dense to medium soils and soft rocks.

- Considering V_{s30} (as per NEHRP guidelines) for ground response analysis studies is found suitable only the SWV of the various layers of soil in the subsurface do not vary significantly from each other and presents a nearly homogeneous media. On the contrary, if there is a noticeable variation of SWV in the layered subsurface, which is the most common scenario, a noticeable underestimation or overestimation is conceived between the assessed V_{s30} and the actual SWV obtained at different depths from MASW survey. The deduced site-classification can lead to misinterpretation and misrepresentation of the actual site characteristics if there is a recognizable layered heterogeneity. Accordingly, an actual relatively stiffer stratum may be erroneously recognized as a softer stratum, and vice-versa, if the V_{s30} is considered for GRA studies and such scenario can yield significantly underestimated or overestimated responses. Hence, it is recommended not to use V_{s30} for ground response analysis or soil-structure interaction studies.
- Instead of adopting V_{s30} as the indicator of site classification that considers averaging of the SWV over the entire 30 m depth, it is recommended to use average SWV over specific depth intervals. As per the present study, it is recommended that averaging SWV over every 5 m depth from the ground surface provides a closer approximation to the actual SWV profile. Hence, it is recommended that NEHRP site classes to be followed for developing a depth-varying contour of site classes of a specific site based on the average SWV computed for every 5 m depth interval. Such depth contour would aid in choosing the proper site class for soil-structure interaction studies depending on the depth at which the foundation would be located within the subsurface.

- It is important to decipher the contribution of various subsurface layers in local amplification or attenuation at different depths of the subsurface. In this regard, contour maps of amplification factor are prepared for each 5 m depth interval (i.e., 0-5 m, 5-10 m, 10-15 m, 15-20 m, 20-25 m, and 25-30 m) from the ground surface. This would aid to understand the influence of actual variations of SWV below the ground level and would aid in proper planning and design of foundation in regard to soil-structure interaction.
- Spatial contour maps generated for different depth layers further revealed significant localized variations, critical for realistic seismic site response analysis. The study recommends adopting depth-specific SWV profiling over conventional V_{s30}-based classification for accurate seismic design, urban planning, and microzonation efforts in seismically vulnerable areas.

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Data Availability Statement

Data associated with the study will be available from the corresponding author upon a reasonable request

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Informed Consent: For this type of study, formal consent is not required.

Author Contributions: AKA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing –original draft, Writing – review and editing; **JT:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Software, Supervision, Writing-Reviewing and Editing; **SSK:** Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing – review and editing; **AD:** Conceptualization, Methodology, Supervision, Writing – review and editing.

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