Shear Wave Velocity measurement from different approaches and its effects on seismic site classification

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ABSTRACT: Knowledge of the dynamic response of subsurface strata is necessary to model the dynamic behaviour of structures during earthquakes. This necessitates the determination of dynamic properties of the soil and seismic site classification, which needs in-situ and laboratory testing. The main objective of this study is to compare seismic site classification by drilling boreholes with Standard Penetration Test (SPT) N value measurement along with hammer energy recordings at positions below the anvil and above the split spoon sampler, measuring shear wave velocity (V_s) by seismic surface wave method of Multichannel Analysis of Surface Wave (MASW) and seismic borehole method of Crosshole (CH) testing at the same sites in India. SPT N values are corrected considering energy below the anvil and above the sampler, and then the same is used to estimate V_s values and to arrive at the seismic site classifications. Additionally, the V_s profile of the same site is compiled from MASW and CH measurement and used to determine the seismic site classifications. Three types of seismic site classifications are adopted in this study, the first one is 30 m average as per the widely used conventional method; second, average V_s values up to engineering bedrock for shallow bed rock sites; and third, V_s values up to layer having V_s of 1500 m/s. Field experiment and different V_s values measured by the two methods are discussed and compared. Further, the difference in seismic site classification when energy-corrected N values are used, and different ways of V_s measurement are presented.

Keywords: Site classification, SPT-N, Hammer energy MASW, Crosshole test

1. Introduction

During an earthquake, local geology plays a significant role in controlling the surface effects of earthquakes. The characteristics of the subsurface soil may alter the amplitude, frequency, and duration of bedrock motion when reaching the surface. This phenomenon is known as the local site effect and can result in excessive ground shaking, liquefaction, and landslides causing additional damage. Before assessing the hazard risk at any site, it is important to determine the dynamic subsurface properties and seismic site classification. This will allow for adequate ground response estimation in the event of any future seismic event.

With the improvement in seismic site classification methods, several studies are coming up considering various regional characteristics influencing the local behaviour of subsoil. At present, the Standard Penetration Test (SPT) N value and Shear wave velocity (V_s) are important parameters for site characterization and site effect assessment. Shear wave velocity can be determined from either surface or borehole methods. It has been observed that the surface method provides more global information than borehole methods. In contrast, the borehole methods are localized [1]. Hence, there should be some difference between the measurements obtained from the two different types of methods [1]. In this study, standard penetration test (SPT) data from five sites in Chennai and two boreholes at one site at IISc Bangalore campus are analyzed. Crosshole survey has been carried out at each site at a depth interval of 1.5m up to 39m depth. MASW survey has been performed at the same locations and the results have been compared with Crosshole and SPT.

Survey sites are classified by seismic site characterization in four approaches in this study. (1) by using the conventional average SPT N value up to 30 m depth [2], (2) by considering 30 m average V_s (V_s^{30}) [3] (3) by considering the average velocity up to the engineering bedrock [4] and (4) by considering the average V_s up to the layer where $V_s \geq 1500 m/s$ [5].

The influence of selection of test method and classification criteria is studied and comparison between the classification obtained using different methods is presented in this paper.

2. Site classification methodology

Indian standard IS 1893: 2016[6] uses the average Standard penetration Test (SPT) N values for site classification. The soil and rock sites are divided into three categories namely Soft soils (N<10), medium or stiff soils (10<N<30) and Hard soils or rocks (N>30). This method does not take into account the fact that the soil profiles can and will have large variations in the areal extent. Then it becomes extremely difficult to decide upon the N value to be used for deciding the soil profile type, which may include deep soil basins, sediment deposits, and presence of weathered rocks among many others. Moreover, since N values are heavily affected by several factors, as discussed later in section 4.1, the method does not provide a reliable estimate of the subsoil behaviour. National Earthquake Hazard Reduction Program (NEHRP)[7] has also provided site classification based on N values which include dense soil, soft rocks (Class I, N>50), Stiff soil (Class II, 15<N<50) and soft soils (Class III, N<15). This classification is different from NEHRP classification based on N-values (Table 1). The boundary N-values for NEHRP classification is taken as 15 and 50 instead of 10 and 30.

Site classification based on average shear wave velocity in a region is getting worldwide attention. There are different ways in which shear wave velocity (V_s) can be used to classify regions. 30m average V_s, called V_s^{30}[3] is commonly used. It has been found that dynamic response predicted by V_s^{30} is reliable and economical estimation, and well correlated with the field observations.

$$V_s^{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{d_i}{v_i}\right)} \qquad (1)$$

Where d_i - the thickness of the ith soil layer in metres; v_i - shear wave velocity for the ith layer in m/s and N – no. of layers in the top 30 m soil strata which will be considered in evaluating V_s^{30} values. V_s^{30} is extensively used for seismic site characterization and amplification parameters estimation. However, often it is observed that obtaining V_s profile up to required 30 m of depth is often difficult and expensive for low-budget projects[8]. Site classification based on NEHRP recommendation is given in Table 1.

Table 1. Site classification based on V_s^{30} (NEHRP)

Site class	General description	V_s^{30} (m/s)	N^{30}
A	Hard rock	≥ 1500	
B	Rock	$760 \leq V_s \leq 1500$	
C	Very dense soil and soft rock	$360 \leq V_s \leq 760$	N>50
D	Stiff soil 15 ≥ N ≥ 50 or 50 kPa ≥ Su ≥ 100 kPa	$180 \leq V_s \leq 360$	15<N<50
E	Soil or any profile with more than 3 m of soft clay defined as soil with PI > 20, w > 40% and Su < 25 kPa.	$V_s \leq 180$	N>50
F	Soils requiring site-specific evaluations		
Note: N: SPT blow count, Su: Undrained shear strength, PI: Plasticity index, w: water content			

Another way of classification is based on the average V_s up to the depth of engineering bedrock ($V_s = 760m/s$) for shallow bedrock region [4]. This particular method is useful in cases where soil thickness is less and rock velocity alters average shear wave velocity considerably when 30m depth is considered. In such cases, extrapolating V_s may not be a proper practise because of possible overestimation.

A new way of classification of shallow and deep soil sites (Table 2) based on average V_s up to the layer having $V_s = 1500m/s$ was proposed by Bajaj and Anbazhagan[5] based on their analysis of site amplification of the input ground motion at various depths. It was observed that this new classification provided a reliable estimation of site amplification factors at deep and shallow soil sites.

Table 2. Site classification based on average up to the layer having $V_s = 1500m/s$[5]

S. No.	Site Class	$V_{S1500,av}$
1	SC1	$350 \leq V_{S1500,av} < 700$
2	SC2	$700 \leq V_{S1500,av} < 900$
3	SC3	$900 \leq V_{S1500,av} < 1100$
4	SC4	$V_{S1500,av} \geq 1100$

3. Study Area

The tests have been performed at five locations in Chennai city and one location at Indian Insititute of Science (IISc), Bangalore, India. Chennai is located on the southeast coast of India and in the northeast corner of the state of Tamil Nadu. It is located on a flat coastal plain known as the Eastern Coastal Plains. The city has an average elevation of 6 m (20 ft), its highest point being 60 m (200 ft). The geology of the city comprises mostly clay, shale and sandstone. The city is classified into three regions based on geology, sandy areas, clayey areas and hard-rock areas. Sandy areas are found along the river banks and the coasts. Clayey regions cover most of the city. Hard rock areas are mostly found in the southern part of the city.

The SPT data obtained from the borelogs along with the site names are presented in Fig. 1. The rebound was considered when N value reached 100 before the required 30cm penetration and such depths were assigned N=100. For IISc campus, two boreholes were drilled at the site and N values were recorded at 1m depth interval. The depth where N=50 was obtained was considered as the depth for the rebound as per the Indian Code [6].

4. Exploration methods used

4.1. Standard Penetration Test (SPT)

SPT is the most common geotechnical and geophysical exploration test carried out worldwide. The test is popular because it is easy to practise and the results are correlatable to various dynamic properties. The N value obtained is a measure of the penetration resistance of the soil in given in-situ conditions. This data can be used to estimate the net bearing capacity. This test has been repeatedly used by researchers to develop relations for the evaluation of various subsurface dynamic properties, ground response analysis and liquefaction assessment.

In spite of the ease of workability of the test, SPT results are not considered absolute because they depend on several factors such as hammer energy transferred from anvil to the sampler, overburden pressure, rod dimensions, anvil shape, fine particle content in the soil, borehole diameter, etc. These factors are accounted through the corrections applied to the measured N value. The energy efficiency of the SPT hammer is fundamental to obtaining the correct SPT data for a given location [9]. Since the major correlations with dynamic properties are developed based on the 60% hammer efficiency, it is important to measure the hammer energy delivered at every test point and correct the reading accordingly. In this study, SPT N values are measured at all sites along with hammer energy first time in India, even though hammer energy is not part of Indian Standard SPT testing recommendation [6].

4.2. MASW survey

MASW is a seismic exploration method which assists in evaluating ground stiffness by measuring V_S profile of the subsurface. MASW utilises the Rayleigh waves generated from an artificial seismic source such as a sledgehammer and recorded on a multichannel record, calculates their velocities and then estimates the V_S the profile below the survey area. The phase velocities observed at different receivers are then plotted against the frequency in the dispersion image and a dispersion curvey is extracted based on the maximum amplitude in the image. Here, dispersion is the phenomenon by which waves of different frequencies travel at different velocities and penetrate different depths because of different wavelengths. The dispersion curve obtained is the put into an iterative inversion analysis and the shear wave velocity profile is obtained using least square approach[10]. The profile obtained is indicative of the V_S profile at the middle of the geophone array[11].

MASW survey has been extensively used for determining site amplification characteristics and developing a regional correlation of SPT-N with various in-situ static and dynamic properties[12].

4.3. Crosshole Test (CH)

Crosshole test is a low strain test and is known for its high-resolution seismic velocity results across the complete borehole depth. Acquiring crosshole seismic data resolves hidden layer velocity anomalies that cannot be detected with conventional surface methods. The velocities obtained can be used to determine other subsurface properties such as low strain shear modulus, Poisson's ratio and elastic modulus.

The test is performed following the technical standard ASTM D4428/D4428M-14[13]. Researchers have been able to successfully use the crosshole test to resolve low-velocity layers of varying thickness, to check the effect of smearing of velocities at interfaces[14] and to determine the variation of soil cover composition with depth[15]. The major factors affecting the crosshole test results are borehole spacing and the depth interval at which the readings are recorded.

5. Field data acquisition

Hammer energy measurement was carried out during SPT at all six locations. The hammer energy was measured using the SPT Hammer energy measuring apparatus (SPT-HEMA) [16] developed by the civil engineering department, IISc Bangalore.

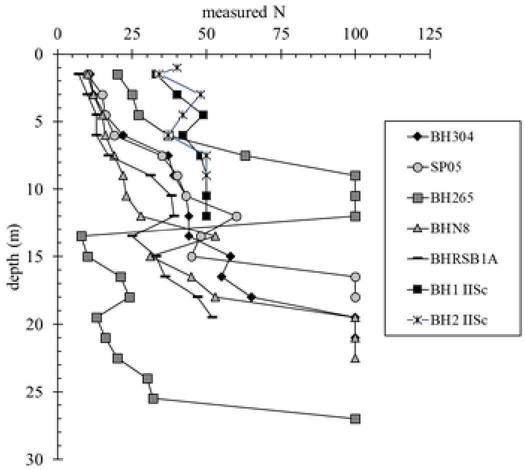

Fig. 1. SPT data obtained from the borelogs at the test sites

Crosshole test was carried out at five sites in Chennai and one site at IISc campus. Geotomographie BIS SH source was used for generating horizontally polarised shear waves and BKG5 receiver with 5 geophones (4 horizontal spaced at 45° and one vertical) was used in the receiver borehole. The data acquisition was carried out using the 24-channel Geode seismograph. Three impulses were stacked together to generate one data file. After one data at depth was recorded, the source was rotated by 180°, thus enabling the signals to be recorded with opposite polarity. This method, popularly known as the crossover method, helps in the detection of the shear wave with enhanced accuracy because of 180° phase reversal (Fig. 2).

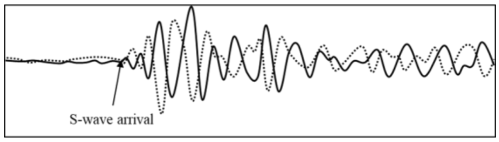

Fig. 2. Crossover method showing the detection of S-wave arrival time

Active MASW survey was carried out with 12 geophones of 2Hz frequency placed at a spacing of 1m. For the active survey, the strike plate was kept at the distance of 3m, and then 5m from the first receiver. The strike plate was hit with a sledgehammer of 8kg weight. For the passive survey, ambient vibration along the roadside was used to generate a dispersion image. Then the dispersion curve was extracted from the dispersion image and inversion analysis was carried out. A typical dispersion curve and final velocity profile are shown in Fig. 3(a) and 3(b).

In Chennai, 40m depth of subsurface was mapped while at IISc, 20m depth was mapped. The depth of mapping was selected in coherence with the borehole depth.

6. Results

V_S profile was obtained from MASW and CH tests and N profile from the SPT. The previously discussed site classification criteria were employed and sites were classified, as discussed in the following sections.

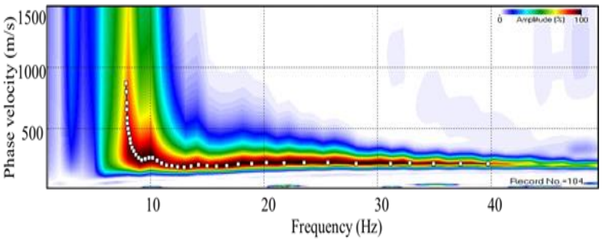

Fig. 3(a). A typical dispersion image and dispersion curve obtained from MASW

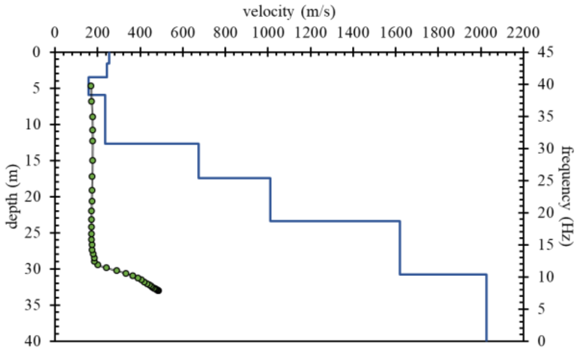

Fig. 3(b). A typical V_s profile obtained from inversion analysis

6.1. Site classification from SPT data

None of the SPT profiles obtained extends to 30m. So, all the layers below the last recorded SPT data are assumed to have the N value equal to the last record. Four of the sites have N value equal to 100 as the last depth, but one site has N = 52. However, beyond that, the observed strata consist completely weathered charnockite, which in all the other boreholes has shown N=100, thus N-value of 100 is assumed to extend up to 30m for this site as well.

Table 3. Site classification based on SPT

Site	N^{30} value	Site class	
		IS 1893	NEHRP
BH304	47	I	D
SP05	50	I	C
BH265	36	I	D
BHN8	42	I	D
BHSB1A	40	I	D
IISc	44	I	D

Energy measurement was carried during SPT and the recorded energy level was used to correct the N-value for site classification. Hydraulic drilling machines were used at each site for the SPT purpose and it was observed that only 45% hammer energy could be imparted in the blows as against the assumed 60%. This observation is important in understanding the role of hammer energy measurement during the SPT. After correction, the N-values reduced because of the increased energy efficiency. After correcting for energy, the average N-values are used for classifying the survey sites and the classification is shown in Table 3.

6.2. Site Classification from Crosshole survey

V_s profiles obtained from the Crosshole tests were analyzed and average velocities up to different depths were evaluated. The average V_s obtained from different methods along with classification predicted are shown in Table 4.

Table 4. V_s and site class obtained from CH survey

Site	V_s^{30} **(m/s)**	**class**	$V_s^{bedrock}$ **(m/s)**	$\overline{V_s}$ **upto 1500 m/s layer (m/s)**	**class**
BH304	330	D	183	229	SC1
SP05	290	D	216	277	SC1
BH265	189	D	196.	212	SC!
BHN8	373	D	235	358	SC1
BHSB1A	286	D	199	274	SC1
IISc	471	C	352	_	_

It can be observed clearly that all the sites fall in site class D. It is to be noted that V_s^{30} for IISc site could not be determined from CH test data because the maximum borehole depth was 20m. Hence, an extrapolation scheme suggested by Boore[8] was employed in this case. The scheme suggests:

$$V_s^{30} = \frac{30}{tt(d)+\frac{30-d}{V_{eff}}} \tag{2}$$

where. $V_{eff}$is the assumed effective velocity from depth d to 30 m (generally assumed to be the velocity at the bottom of velocity profile available, i.e. $V_{eff} = V_s(d)$) and $tt(d)$ is the travel time to depth d, given by $tt(d) = \int_0^d \frac{dz}{V_s(z)}$. $V_s^{30} = 471m/s$ was found using this scheme, and hence, site class C was suggested as per NEHRP. However, this method underestimates the V_s^{30} and has been observed to have a bias towards the lower site classes. No layer with the $V_s \geq 1500m/s$ was found during CH survey.

6.3. Site classification from MASW survey

Table 5 shows the average velocities obtained using MASW at the survey sites. The difference in the velocity and site classification obtained from CH and MASW is highlighted. This discrepancy could probably be attributed to:

1. CH test gives the velocity distribution between the two boreholes and MASW gives an average velocity profile at a single point.
2. The MASW method takes average velocities for several depths at a time whereas the CH method gives velocity at each survey depth, thus the difference is obvious.

The average V_s up to the 1500 m/s velocity layer is not available at IISc site because even after 100 m mapping of subsurface, V_s was not found to exceed 1200m/s. Site classification based on MASW is presented in Table 5.

Table 5. V_s and site class obtained from MASW survey

Site	V_s^{30} (m/s)	class	$V_s^{bedrock}$ (m/s)	$\overline{V_s}$ upto 1500 m/s layer (m/s)	class
BH304	448	C	293	373	SC1
SP05	378	C	261	400	SC1
BH265	382	C	352	438	SC!
BHN8	398	C	328	406	SC1
BHSB1A	374	C	241	382	SC1
IISc	517	C	382	_	_

7. Conclusions

Shear wave velocity (V_s) profiles for subsurface at six sites have been determined using MASW and Crosshole survey. These surveys were preceded by SPT and N-values along with V_s was used to determine the seismic site class for the six locations. It was observed that the site class obtained from different methods differ are different. The difference could have been possible because of the methodology and the working principle of the employed methods. These differences need to be taken into account while selecting a suitable method to determine site class. Selection of site class based on different average V_s has also been presented. Selection of appropriate average $V_s$should be decided based on the importance and need of the facility for which the survey is being carried out.

This work also emphasises that only one study for determining regional site classification is not sufficient and different site investigation methods should be used in an integrated manner to obtain the correct regional data.

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