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# Seismic Site Classification and Correlation between Standard Penetration Test N Value and Shear Wave Velocity for Lucknow City in Indo-Gangetic Basin

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*Abstract*—Subsurface lithology and seismic site classification of Lucknow urban center located in the central part of the Indo-Gangetic Basin (IGB) are presented based on detailed shallow subsurface investigations and borehole analysis. These are done by carrying out 47 seismic surface wave tests using multichannel analysis of surface waves (MASW) and 23 boreholes drilled up to 30 m with standard penetration test (SPT) N values. Subsurface lithology profiles drawn from the drilled boreholes show low- to medium-compressibility clay and silty to poorly graded sand available till depth of 30 m. In addition, deeper boreholes (depth >150 m) were collected from the Lucknow Jal Nigam (Water Corporation), Government of Uttar Pradesh to understand deeper subsoil stratification. Deeper boreholes in this paper refer to those with depth over 150 m. These reports show the presence of clay mix with sand and Kankar at some locations till a depth of 150 m, followed by layers of sand, clay, and Kankar up to 400 m. Based on the available details, shallow and deeper cross-sections through Lucknow are presented. Shear wave velocity (SWV) and N-SPT values were measured for the study area using MASW and SPT testing. Measured SWV and N-SPT values for the same locations were found to be comparable. These values were used to estimate 30 m average values of N-SPT ($N_{30}$) and SWV ($V_s^{30}$) for seismic site classification of the study area as per the National Earthquake Hazards Reduction Program (NEHRP) soil classification system. Based on the NEHRP classification, the entire study area is classified into site class C and D based on $V_s^{30}$ and site class D and E based on $N_{30}$. The issue of larger amplification during future seismic events is highlighted for a major part of the study area which comes under site class D and E. Also, the mismatch of site classes based on $N_{30}$ and $V_s^{30}$ raises the question of the suitability of the NEHRP classification system for the study region. Further, 17 sets of SPT and SWV data are used to develop a correlation between N-SPT and SWV. This represents a first attempt of seismic site classification and correlation between N-SPT and SWV in the Indo-Gangetic Basin.

**Key words:** Subsurface lithology, site classification, deep basin, NEHRP, MASW, SPT.

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## 1. Introduction

During an earthquake, local geology plays a significant role in controlling the surface effects of earthquakes. Subsurface soil properties can change the amplitude, frequency, and duration of bedrock motion when it reaches the surface. This phenomenon is known as the site effect and can cause additional damage during an earthquake in the form of excessive ground shaking, liquefaction, and landslides. Numbers of examples are available in the literature where local soil led to more damage during earthquakes in India (Rajendran *et al.*, 2003; Ambraseys and Bilham, 2003; Khan, 1874; Oldham, 1883; Mahajan and Virdi, 2001; Bendick *et al.*, 2001; Nihon, 2011).

A thick soil deposit with high water table is at heavy risk of undergoing excessive settlement and liquefaction during an earthquake. Before assessing these hazards, it is necessary to understand the geology of the region by focusing on subsurface soil characteristics and stratification details. This will help to understand the local site effects and induced effects accurately, so that such effects during any future earthquake can be precisely forecasted. The roles of locally available soil in modifying seismic waves are inevitably reflected in modern seismic codes. The determination of appropriate elastic response/design spectra according to soil categories and seismicity/site classification based on SPT-N and SWV is the simplest way to account for site effects in both engineering projects and for general purposes such as microzonation studies (Pitilakis, 2004). It is also relevant to remember that these kinds of parameters concern only the elastic behavior of soils. Thus, for a more complete microzonation study, it is indispensable to perform regular tests on extracted soils. However, limited attempts have been conducted for seismic site classification and to understand site effects for different soil deposits in India. Further, no such studies have been carried out particularly in the IGB, which is composed of thick alluvial deposits.

In the present work, subsoil investigation of Lucknow City, part of the Indo-Gangetic Basin, was attempted using the seismic surface wave technique of MASW and drilled boreholes. MASW testing was carried out at 47 locations covering almost the entire Lucknow City, with approximately one test in each 2 km $\times$ 2 km grid. Of these locations, corresponding to 12 MASW survey locations, boreholes were drilled and N-SPT values were measured with depth. In addition to these, 11 additional boreholes drilled to a minimum depth of 30 m were collected from the same agency. In total, 47 shear wave velocity profiles and 23 boreholes with N-SPT values were used for seismic site classification of the study area. Of these, 17 MASW and SPT data locations were very close to each other. SWV and SPT-N profiles for these 17 locations were used to develop the correlation between measured SWV and SPT-N values.

## 2. Study Area and Subsurface Lithology

The study area of Lucknow is a densely populated city in the central part of the Indo-Gangetic Basin. The basin was formed by the collision of the Indian and Asian Plates during the Cenozoic Era, similar to the origin of the Himalayas. In addition to the rise of the Himalayas due to this collision, accumulation of thick fluvial sediments took place due to river-associated erosion processes in the Himalayas. Also, the study area is located in proximity to active Himalayan seismic gap (Fig. 1). It covers an area of about 370 km$^2$, with city centre at Vidhan Sabha having latitude 26°51.6′N and longitude 80°54.6′E. The average elevation of Lucknow is about 128 m above mean sea level. The elevation difference in the entire study area is about 29 m from its highest elevation of 129 m in the area of the Sharda Canal in the central part of Lucknow to its lowest elevation of 100 m in the southeastern Dilkusha Garden in the southern part. The River Gomati flows through the middle of Lucknow from northwest to southeast (Husainabad to Dilkusha Garden). Regional soil deposits mainly comprise both older and younger alluvium of Ganga–Ghagra interfluves (GSI, 2001). The older alluvium spreads over the vast area between elevations 115 and 129 m, covering areas such as Chowk, Aminabad, Charbagh, and Kakori. Sand mounds of height 4–5 m from ground level have been observed in the Malihabad and Gosainganj areas. Very deep boreholes (>1 km) have been conducted by Oil and Natural Gas Corporation (ONGC) at various places in the Indo-Gangetic Basin such as Ujhani, Kasaganj, Tilhar, and Raxual, and these are discussed in detail by Sastri *et al.*, (1971). Lucknow lies between the Tilhar District of Uttar Pradesh and the Raxual District of Bihar. Based on ONGC reports (Sastri *et al.*, 1971), alternate layers of sand and clay with few layers of Kankar in between were found until a depth of 360 m in Kasaganj in the west, further growing towards Raxual in the east from 360 to 700 m, and further dipping down to a depth of about 1,500 m. The presence of limestone was found at 620 m in Kasaganj, further dipping down and reaching a depth of 4,000 m in Raxual. Based on these deep boreholes obtained at these two locations, the approximate depth of limestone at Lucknow has been estimated to be about 1,700 to 2,000 m. Followed by limestone, Vindhyan rocks were observed at depth of about 2,000 m at Tilhar. Based on this information, it can be inferred that the depth of Vindhyan rock may be at approximately 2,200 to 2,500 m at Lucknow.

Jal Nigam (Water Corporation), Government of Uttar Pradesh has performed borings at several locations in Lucknow to observe soil stratification details and fluctuation in water table depth in the area. The depth of these borings ranges from 130 to 400 m, and they are denoted as deep boreholes (DB) in further discussion. Figure 1 shows the location of 20 deep boreholes drilled by Jal Nigam within the study area. To understand the subsurface soil profiles, a cross-section along AA′ in Fig. 1 up to 150 m based on Jal Nigam reports has been developed and is shown in Fig. 2. It has to be mentioned here that the legend used in Fig. 2 was taken from the borehole reports of Jal Nigam. Even though the terms do not follow any standard classification system, the same legend has been used for the preparation of cross-sections. The subsurface profile given in Fig. 2 shows that the most of the study area is covered by surface

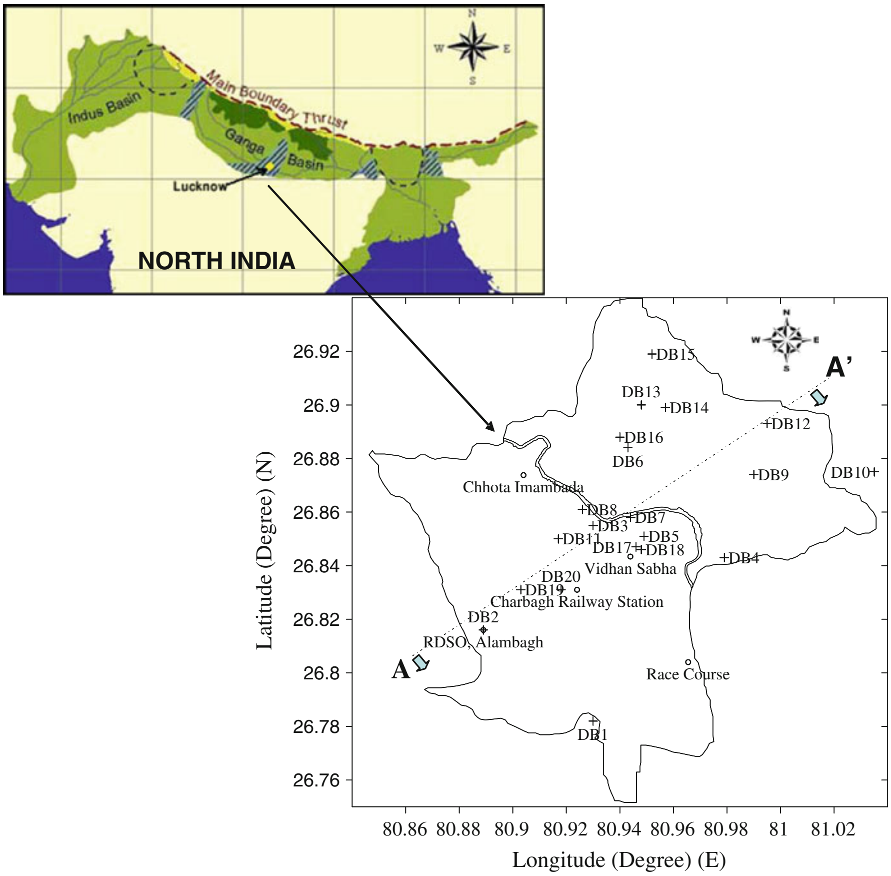


Figure 1
Map of Indo-Gangetic Basin with Lucknow City. DB1–DB20 are deep boreholes obtained from Jal Nigam reports and used to generate deep soil lithology cross-section

deposits of fine sand. The depth of fine sand has been found to be up to 80 m at DB1. This depth decreases from DB1 to DB9 and reaches the surface close to River Gomati (as observed from the left edge in Fig. 2). Similarly the right side of Fig. 2 highlights the presence of clay deposits at DB5 and DB20. In the clay layer, pockets of clay mixed with Kankar were found below the River Gomati at different depths. After DB20, fine sand was noticed at depth of about 10 to 12 m towards DB2. As observed from DB2 in Fig. 2, fine sand followed by clay overlain or mixed with Kankar was found at depth of 130 m below ground level. Traces of medium sand under the clay layer mixed with Kankar were also found at DB2. Since elevation detail for each borehole is not available, Fig. 2 does not show any elevation variation at ground surface. DB20 is the only borehole available till 400 m. Based on stratification details at DB20, medium sand was found at depth of 274 m. Beyond 274 m depth, repeated layers of sand and clay with Kankar mixed with clay are present till 400 m and no bedrock was reported. These observations also concur with Central Ground Water Board (CGWB) studies, where the presence of bedrock was not been found to 298 m in southern part and 445 m in western part of Lucknow City (DRM, 2001).

### 3. Seismicity of the Region

Lucknow, the capital of Uttar Pradesh, lies in seismic zone III of the seismic zonation map of India (IS: 1893, 2002), with peak ground acceleration (PGA) of 0.16*g* at bedrock. The State of Uttar

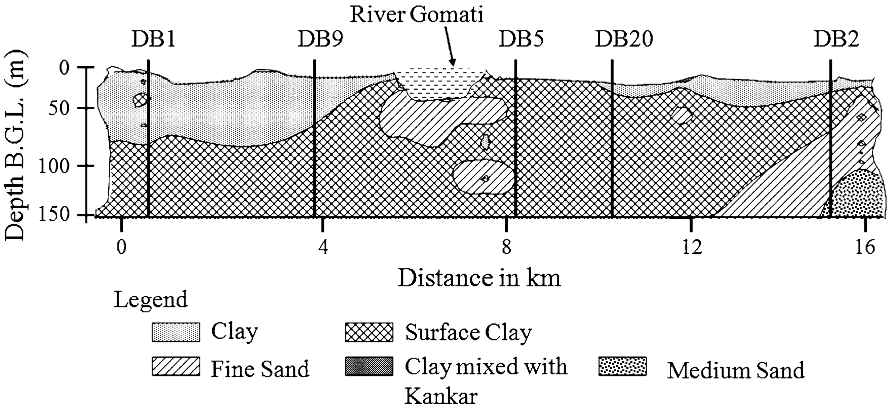


Figure 2
Cross-section through Lucknow City (line AA′ in Fig. 1) based on Jal Nigam borehole reports

Pradesh has faced a number of earthquakes. These include the 1925 Rae-Bareili, 1956 Bulandshahar, 1965 Gorakhpur, and 1966 Muradabad earthquakes. The magnitudes of these earthquakes were in the range of 5.0–6.3 on the Richter scale. The Delhi Haridwar, Delhi–Muzaffarnagar, and Faizabad Faults are major seismic features running beneath Uttar Pradesh. The disaster risk management program of the Ministry of Home Affairs in association with the United Nations Development Program (UNDP) has highlighted that Lucknow City lies above the Faizabad Fault and that this fault has been inactive over the last 350 years. Researchers have highlighted that this fault is under heavy stress due to a probable seismic gap and has the potential to cause a large earthquake in the future (Nadeshda, 2004). As the Himalayas are rising due to subduction of the Indian Plate under the Asian Plate, movement of the Indian Plate by 5.25 m can cause an earthquake as high as magnitude 8 on Richter scale on the Faizabad Fault according to the Earthquake Mitigation Department of Uttar Pradesh (Nadeshda, 2004). Apart from the local seismic activity around Lucknow, the area also lies within a radial distance of 350 km from Main Boundary Thrust (MBT) and Main Central Thrust (MCT), where many major earthquakes are frequently reported. Khattri (1987) highlighted the possible existence of a seismic gap along the Himalayan belt. These two observations clearly show that Uttar Pradesh, in particular the highly populated city of Lucknow, has the risk of earthquake hazards due to two possible seismic gaps. Hence, studies of seismic site characterization and understanding the geotechnical properties are necessary.

### 4. *Seismic Site Classification*

The process of estimating the effects of earthquake due to the presence of soil layers under earthquake loading requires understanding of the subsurface material properties. Recent modern seismic codes in America, Europe, Japan, and worldwide (IBC 2009, UBC 97, NEHRP and EC8) have produced abundant, valuable data and have incorporated site effects. Classification of sites based on any one of the three parameters, i.e., undrained shear strength ($S_u$), standard penetration test (SPT) N values, and shear wave velocity (SWV) values, to evaluate earthquake effects is done by seismic site characterization. The design spectrum of each site determined based on its site class, considering 30 m average shear wave velocity ($V_s^{30}$) values (Borcherdt, 1994), 30 m average standard penetration resistance ($N_{30}$), and undrained shear strength ($S_u^{30}$), are also used for site classification. SWV can be directly measured from field tests or can be estimated from existing correlations between SPT blow counts (SPT-N) and SWV (Hasancebi and Ulusay, 2007). Site classes based on $V_s^{30}$ are useful for future seismic zonation studies, because site amplification factors were defined as a function of $V_s^{30}$, such that the effect of site conditions on ground shaking can be taken into account (Koçkar *et al.*, 2010). In India, a few cities have been classified considering 30 m SWV ($V_s^{30}$), and many more are under investigation. These site classifications are combined with probabilistic seismic hazard approaches to estimate the surface-level hazard values. Surface-level acceleration using the site classes and probabilistic seismic hazard approach was presented by RAGHUKANTH and IYENGAR (2007), ANBAZHAGAN *et al.* (2009), and VIPIN *et al.* (2009). In spite of the strong correlation between top 30 m shear wave velocities and relative amplification, the suitability of these classification schemes for different regions are still under study (MARK *et al.*, 2001, ANBAZHAGAN *et al.*, 2011).

## 5. MASW Survey

Multichannel analysis of surface waves (MASW) is a geophysical method that records Rayleigh waves on a multichannel record. MASW has been widely used throughout the world for seismic site classification and site response studies (PARK *et al.*, 1999; ANBAZHAGAN and SITHARAM, 2008a, b). In India, MASW has been used for microzonation of Jabalpur urban area (PCRSMJUA, 2005), site characterization of Delhi (RAO and NEELIMA, 2007), site classification and site response of Dehradun (MAHAJAN *et al.*, 2007), mapping of rock depth in Bangalore (ANBAZHAGAN and SITHARAM, 2009), microzonation of Bangalore (ANBAZHAGAN *et al.*, 2010), and site classification and site response of Chennai (UMA MAHESHWARI *et al.*, 2010).

The test setup consists of a 24-channel Geode seismograph in combination with 24 vertical geophones with frequency of 4.5 Hz. An impulsive source of a 15-pound sledge hammer striking against a 30 cm × 30 cm steel plate generates the surface waves. In the present work, a geophone interval of 1 m and varying shot distances of 5, 10, 15, 20, and 25 m with 10 stacks were used to reach maximum depth of penetration. A similar survey was carried out at 47 locations within the Lucknow urban center. MASW testing locations are shown in Fig. 3 as solid triangles. Test locations were selected for one test in a grid size of 2 km × 2 km.

A dispersion curve displays a plot of phase velocity versus frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. The shorter wavelengths are sensitive to the physical properties of surface layers (XIA *et al.*, 1999). For this reason, a particular mode of surface wave will possess a unique phase velocity for each unique wavelength, leading to the dispersion of the seismic signal. For a multilayered subsurface model, Rayleigh-wave dispersion curves can be calculated using Knopoff's method (SCHWAB and KNOPOFF, 1972). The Rayleigh-wave phase velocity, $c_{Rj}$, is determined by a characteristic equation $F$ in its nonlinear, implicit form as

$$F(f_j, c_{Rj}, v_s, v_p, \rho, h) = 0 \quad (j = 1, 2, \ldots, m), \qquad (1)$$

where $f_j$ is the frequency in Hz; $c_{Rj}$ is the Rayleigh-wave phase velocity at frequency $f_j$; $\mathbf{v}_s = (v_{s1}, v_{s2}, \ldots, v_{sn})^T$ is the $S$-wave velocity vector, with $v_{si}$ as the shear-wave velocity of the $i$th layer; $n$ is the total number of layers; $\mathbf{v}_p = (v_{p1}, v_{p2}, \ldots, v_{pn})^T$ is the compressive $P$-wave velocity vector, with $v_{pi}$ as the $P$-wave velocity of the $i$th layer; $\rho = (\rho_1, \rho_2, \ldots, \rho_n)^T$ is the density vector, with $\rho_i$ the density of the $i$th layer; and $h = (h_1, h_2, \ldots, h_{n-1})^T$ is the total thickness vector, with $h_i$ the thickness of the $i$th layer. Superscript "T" denotes the vector transpose in given form. Given a set of model parameters ($v_s$, $v_p$, $\rho$, and $h$) and a specific frequency ($f_j$), the roots of Eq. (1) are the phase velocities. If the dispersion curve consists of $m$ data points, a set of $m$ equations in the form of Eq. (1) can be used to find the phase velocities at frequencies $f_j$ ($j = 1, 2, \ldots, m$) using the bisection method (PRESS *et al.*, 1992; XIA *et al.*, 1999). In this study, only the fundamental mode has been considered. The lowest analyzable frequency in this dispersion curve is around 4 Hz, while the highest frequency is 75 Hz. A typical dispersion curve along with signal amplitude and signal-to-noise ratio obtained based on the above analysis using SurfSeis© is shown in Fig. 4.

Shear wave velocity can be derived from inverting the dispersive phase velocity of the surface (Rayleigh and/or Love) wave (DORMAN and EWING, 1962; AKI and RICHARDS, 1980; MARI, 1984; XIA *et al.*, 1999). The shear wave velocity profile was calculated using an iterative inversion process that requires the dispersion curve developed earlier as input. A least-squares approach allows automation of the process (XIA *et al.* 1999). $S$-wave velocities of each layer can be represented as the elements of a

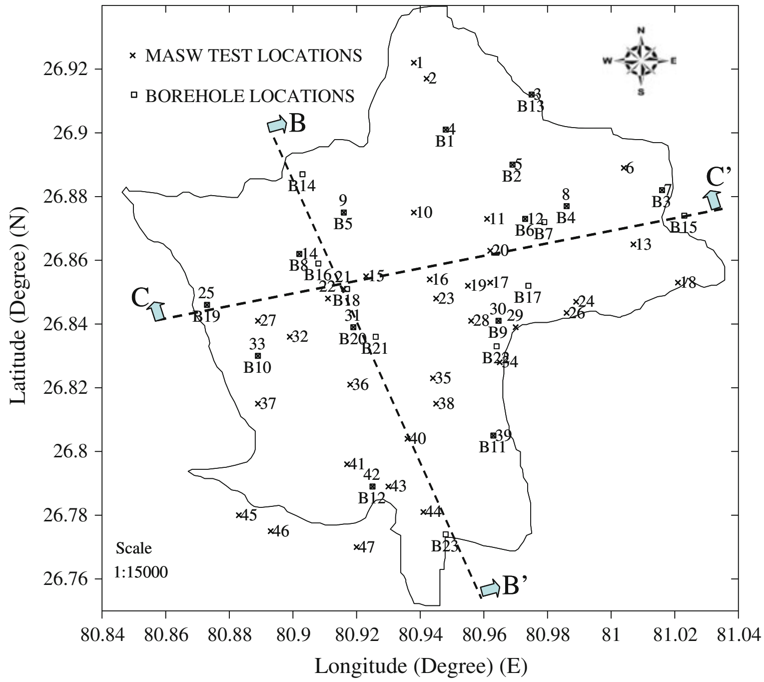


Figure 3
MASW and SPT test locations in Lucknow City: B1–B13 are boreholes with N-SPT values, and 1–47 are MASW locations

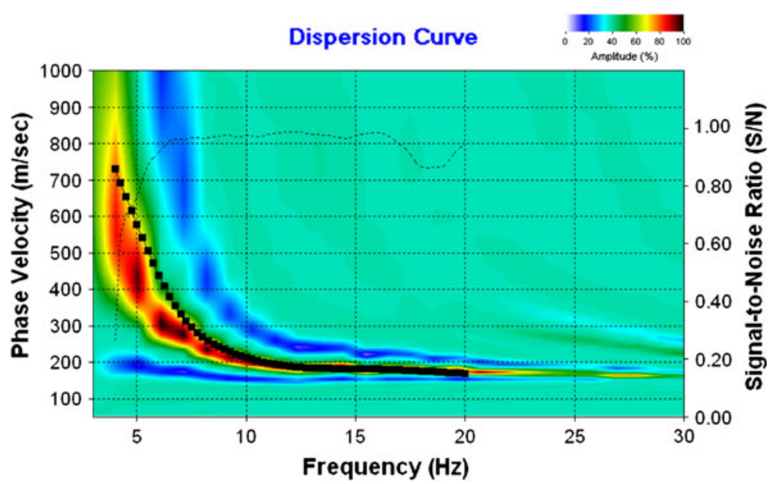


Figure 4
Typical dispersion *curve* for Lucknow soil

vector $\mathbf{x}$ of length $n$, or $\mathbf{x} = [v_{s1}, v_{s2}, v_{s3}, \ldots, v_{sn}]^{\mathrm{T}}$. Similarly, the measurements (data) of Rayleigh-wave phase velocities at $m$ different frequencies can be represented as the elements of a vector $\mathbf{b}$ of length $m$, or $\mathbf{b} = [b_1, b_2, b_3, \ldots, b_m]^{\mathrm{T}}$. Nonlinearity in $\mathbf{c}_{\mathrm{R}}$ can be linearized using Taylor-series expansion and matrix theory as

$$J\Delta X = \Delta b, \tag{2}$$

where $\Delta\mathbf{b} = \mathbf{b} - \mathbf{c}_{\mathrm{R}}(\mathbf{x}_0)$ is the difference between measured data and model response in the initial estimation, in which $\mathbf{c}_{\mathrm{R}}(\mathbf{x}_0)$ is the model response to the initial $S$-wave velocity estimates, $\mathbf{X}_0$; $\Delta\mathbf{X}$ is a modification of the initial estimation; and $\mathbf{J}$ is the

Jacobian matrix (Eq. 2) with $m$ rows and $n$ columns ($m > n$). The elements of the Jacobian matrix are the first-order partial derivatives of $\mathbf{c}_R$ with respect to $S$-wave velocities. Since the number of data points contained in the dispersion curve is generally much larger than the number of layers used to define the subsurface ($m > n$), Eq. (1) needs to be solved by optimization techniques. The objective function for optimization can be defined as

$$\Phi = \|J\Delta X - \Delta b\|_2 W \|J\Delta X - \Delta b\|_2 + \alpha \|\Delta X\|_2^2, \quad (3)$$

where $\| \|_2$ is the $l_2$-norm length of a vector, $\alpha$ is the damping factor, and $\mathbf{W}$ is a weighting matrix. This is a constrained (weighted) least-squares problem. More details about the sensitivity of each parameter and calculation with respective examples are detailed in Xia *et al.* (1999). Shear wave velocities of each location were inverted from respective dispersion curves. After inversion, SWV profiles (variation of shear wave velocity with depth) were obtained with initial and final SWV variation with depth. The obtained variation of SWV with depth is indicative of the SWV variation with depth at the middle of the geophone array. In most cases, a source to first receiver distance of 15 m was found to be optimum to penetrate to a depth of 40 m or more with signal-to-noise ratio above 70 %. Figure 5 shows typical SWV profile of Lucknow soil.

## 6. *Boreholes and Standard Penetration Test*

The MASW test gives shear wave velocity with depth, but site characterization is incomplete without knowledge of subsurface stratum and soil type. The standard penetration test is a widely used in situ test in a borehole to evaluate the geotechnical properties of soil. A split spoon sampler with external and internal diameter of 50 and 35 mm, respectively, and 650 mm long is driven into the soil under the impact of a 63.5-kg hammer from a height of 0.76 m. The sampler is driven to penetrate to a depth of 450 mm. The number of blows required by the sampler to penetrate the last 300 mm of depth is called the N-SPT value. For this study, 12 boreholes of up to 30 m were drilled close to selected MASW survey locations. In addition, data from 11 boreholes with N-SPT values were also collected from the existing database of the drilling agency. These 11 boreholes were drilled to minimum depth of 30 m by the same geotechnical firm engaged to drill the 12 boreholes in the study. These drilling locations were selected to be not close to locations where existing data were available but close to MASW locations. During drilling of the boreholes, the N-SPT was measured and soil samples were also collected as per IS 2131 (1981).

All boreholes were drilled with diameter of 150 mm as per IS: 1892 (1974), and N-SPT values were measured regularly at 1.5-m intervals as per IS: 2131 (1981). Disturbed and undisturbed samples were collected at possible depths as per IS: 2132 (1986). The physical properties were measured in the laboratory using disturbed soil samples as per IS: 1498 (1970) and used for soil classification in this paper. N-SPT values and soil profiles were recorded in the field. In total, the 23 boreholes covered the entire city area reasonably (Fig. 3), being numbered B1 to B23. A typical borelog of Lucknow City is shown in Fig. 6. Variation in water table in the study area during the testing period was observed from 1 to 27 m depth. General soil encountered during boring were silty sand to clay of low compressibility. Measured SPT-N values varied from 3 to 50. Whenever the N-SPT value exceeds 50 for 300 mm penetration, it is treated as refusal (R) and further N-SPT values were not measured for that depth as per IS 2131 (1981). The SPT test is crude and depends on many factors, due to the variations in the procedure and equipment used when performing the test. Various factors include the drilling methods, type of drill rods used, borehole sizes and stabilization methods, sampler used, adopted blow count rate, hammer configuration, energy corrections, fines content, and testing procedures (Schmertmann and Palacios, 1979; Kovacs *et al.*, 1981; Farrar *et al.*, 1998; Sivrikaya and Togrol, 2006). The combined effect of all of these factors can be accounted for by applying correction factors separately or together (Anbazhagan and Sitharam, 2010). However, limited attempts have been made to evaluate these corrections for Indian soil condition and drilling practice (Anbazhagan *et al.*, 2012). Hence, measured N-SPT values were directly used here for site classification and correlation.

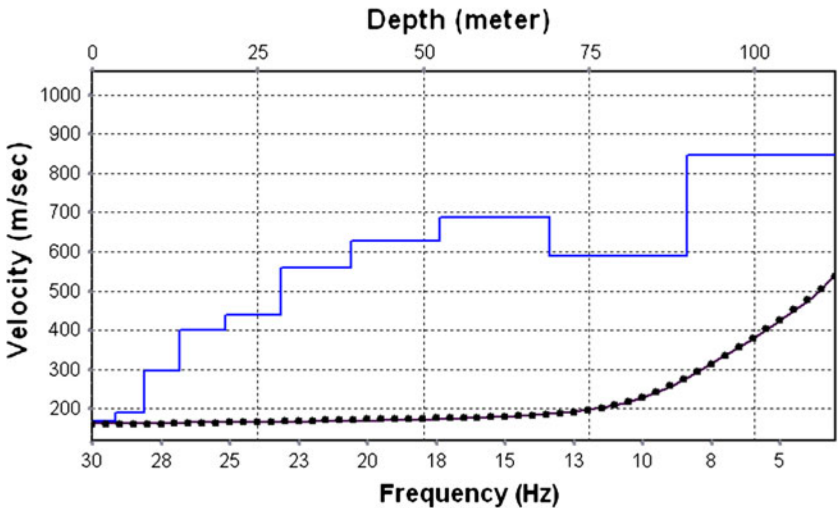


Figure 5
Typical shear wave velocity profile for Lucknow soil

The lithology profiles through lines BB′ and CC′ marked on Fig. 3 using borehole data are shown in Fig. 7a and b, respectively. Figure 7a indicates the presence of silty sand and poorly graded sand (SM-SP) in most of the cross-section. Other portions of the cross-section are occupied by low- to medium-compressibility clay (CL-CI). River Gomati comes in between B16 and B14. Small traces of low-compressibility silt (ML) can also be found under B20. Clay deposit was encountered below the river course till depth of 30 m, as shown in Fig. 7a. Since the actual elevation difference has not been recorded, these cross-sections are drawn considering the same elevation across Lucknow. Figure 7b shows the cross-section through CC' in Fig. 3. In this section, layers of low-compressibility clay (CL) have been found as surface layer at both ends. Middle portions are covered by silty sand and poorly graded sand (SM-SP), which continues from surface till 30 m or more. Small traces of silts (ML) were found under B7. River Gomati is occupied by sand substrata, however the presence of clay can also be seen adjacent to the sandy layer. All the cross-sections have been drawn based on the borehole data. In both Fig. 7a and b, it can be observed that the major portion of the subsurface is covered by sand and clay mixed with silt. The cross-section based on deeper boreholes as given in Fig. 2 also shows the presence of clay and sand. Presence of Kankar layer was encountered after 40 m depth, as shown in Fig. 2. Stratification details obtained from all three cross-sections were found to be comparable in terms of soil type and layer thickness for each soil type.

## 7. *Site Classification for the Study Area*

The equivalent shear stiffness values of soil based on SPT-N or SWV over 30 m depth can be calculated by

$$N_{30} \text{ or } V_{\mathrm{s}}^{30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \left( \frac{d_i}{N_i \text{ or } V_{s_i}} \right)}, \tag{4}$$

where $\sum d_i =$ cumulative depth in meters, and $d_i$, $v_i$, and $N_i$ denote the thickness (m), shear-wave velocity, and SPT-N not exceeding 100 blows/0.3 m as directly measured in the field without corrections of the $i$th formation or layer, respectively, in a total of $n$ layers within a depth of 30 m. To classify the study area, SPT-N and shear wave velocity values in the following ranges suggested by NEHRP (BSSC, 2003) were considered: site class A ($V_{\mathrm{s}}^{30} > 1.5$ km/s), site class B ($0.76$ km/s $< V_{\mathrm{s}}^{30} \leq 1.5$ km/s), site class C ($0.36$ km/s $< V_{\mathrm{s}}^{30} = 0.76$ km/s or $N_{30}$), site class D ($0.18$ km/s $< V_{\mathrm{s}}^{30} \leq 0.36$ km/s or $15 \leq N_{30} \leq 50$), and site class E ($V_{\mathrm{s}}^{30} < 0.18$ km/s or $N_{30} < 15$).

BH No B-3 Date of commencement 17.2.10
Ground Water Table 2.5m Below Ground Level Date of completion 19.2.10

| Soil Description | Thickness of layer | soil classification |
|---|---|---|
| SILTY-CLAY | 3.0 | CL |
| SILTY-CLAY | 9.0 | CI |
| SILTY-CLAY | 1.5 | CL |
| SILTY-CLAY | 6.0 | CI |
| SILTY-CLAY | 0.8 | CL |
| SILTY-SAND | 4.5 | SM |
| SILTY-CLAY | 5.2 | SM-SP |

Depth Below GL(m): 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, 24.0, 25.0, 26.0, 27.0, 28.0, 29.0, 30.0

| Samples Type | Depth (m) | SPT N values |
|---|---|---|
| DS | | |
| UDS SPT | 2.3 | N=7 |
| UDS SPT | 3.8 | N=10 |
| UDS SPT | 5.3 | N=14 |
| UDS SPT | 6.8 | N=14 |
| UDS SPT | 8.3 | N=15 |
| UDS SPT | 9.8 | N=16 |
| UDS SPT | 11.3 | N=14 |
| UDS SPT | 12.8 | N=18 |
| UDS SPT | 14.3 | N=21 |
| UDS SPT | 15.8 | N=20 |
| UDS SPT | 17.3 | N=19 |
| UDS SPT | 18.8 | N=20 |
| UDS SPT | 20.3 | N=19 |
| UDS SPT | 21.8 | N=22 |
| UDS SPT | 23.3 | N=23 |
| UDS SPT | 24.8 | N=23 |
| UDS SPT | 26.3 | N=24 |
| UDS SPT | 27.8 | N=22 |
| UDS SPT | 29.3 | N=26 |
| UDS | | |

Note
Bore hole Terminated at 30.0m
R-Rebound
DS-Disturbed Sample
SPT-Standard Penetration Test
UDS- Undisturbed Sample
GL- Ground level

Figure 6
Typical borelog with SPT N values for Lucknow

The SWV profiles measured at 47 locations in the MASW survey were used to estimate $V_s^{30}$. Measured SWV were available for more than 30 m at most of the locations, except one location where the extrapolation scheme given by Boore (2004) was used. As per Boore (2004), either the SWV of the lowest layer is considered to be continued till 30 m depth to calculate $V_s^{30}$ or it can be estimated using Boore's (2004) correlation between $V_s^{30}$ and average SWV till a depth of $d$ ($V_s^d$). Since only one borehole had profile available for less than 30 m, the SWV of the lowermost layer was assumed for the rest of the depth.

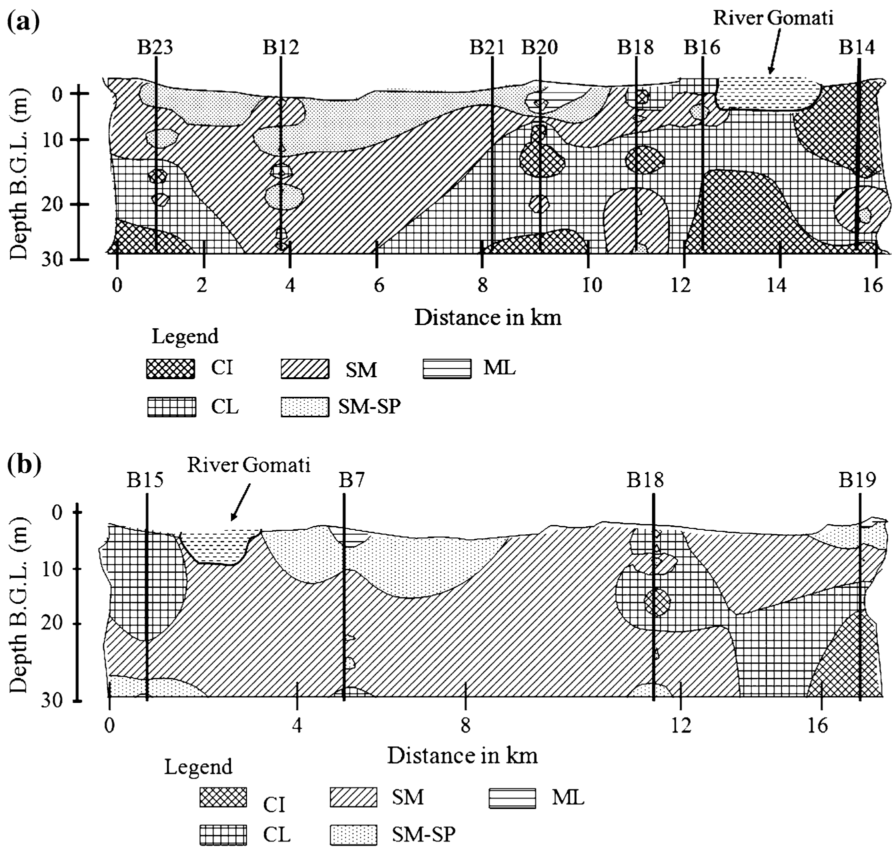


Figure 7

Lithology cross-section up to 30 m considering drilled boreholes: **a** section through line BB′ in Fig. 3 and **b** section through line CC′ in Fig. 3

Calculated $V_s^{30}$ varied from 230 to 470 m/s, and these values were grouped according to the site classes as per NEHRP. Using the Krigging interpolation technique, the values for intermediate locations were obtained and mapped for the study area. Figure 8 shows the $V_s^{30}$ distribution in Lucknow. It can be noticed that the entire area comes under site class D, with small areas falling under site class C.

Site class C is noticed in four areas in the study area, with $V_s^{30} > 360$ m/s, located on the outskirts of Lucknow. Around 17 % of the total data shows site class C. SWV profiles at these locations (Fig. 9) indicate the presence of stiff soils (180 m/s $\leq$ SWV $\leq$ 360 m/s) till a depth of 12 m, which changes to dense soil or soft rock (360 m/s $\leq$ SWV $\leq$ 760 m/s) till 30 m depth. Again it can be seen from Fig. 8 that most of the city belongs to site class D, having 30 m average shear wave velocity ranging from 180 to 360 m/s. Selected SWV profiles corresponding to site class D are shown in Fig. 10. These profiles show SWV of <360 m/s (loose to medium soil) to depth of 23 m at most of the locations. Other locations show dense soil up to 10 m followed by loose to medium soil. Thus, alternating bands of dense and medium soils are encountered at these locations.

In addition, 23 drilled borelog datasets of N-SPT values were used for site classification. Equation 4 was used to calculate 30 m average N-SPT values, which are superimposed on the SWV site classification map in Fig. 8. Due to the limited available spatial data for SPT-N, separate $N_{30}$ contours for Lucknow have not been developed. Based on 30 m average N-SPT values, Lucknow can be classified as site class E and D. The average N-SPT values are <15 in the top 15 m for site class E profiles. It can be noticed that the N-SPT-based site classification differs from the SWV classification by about 50 %. Here, mismatch of site classes based on $V_s^{30}$ and $N_{30}$

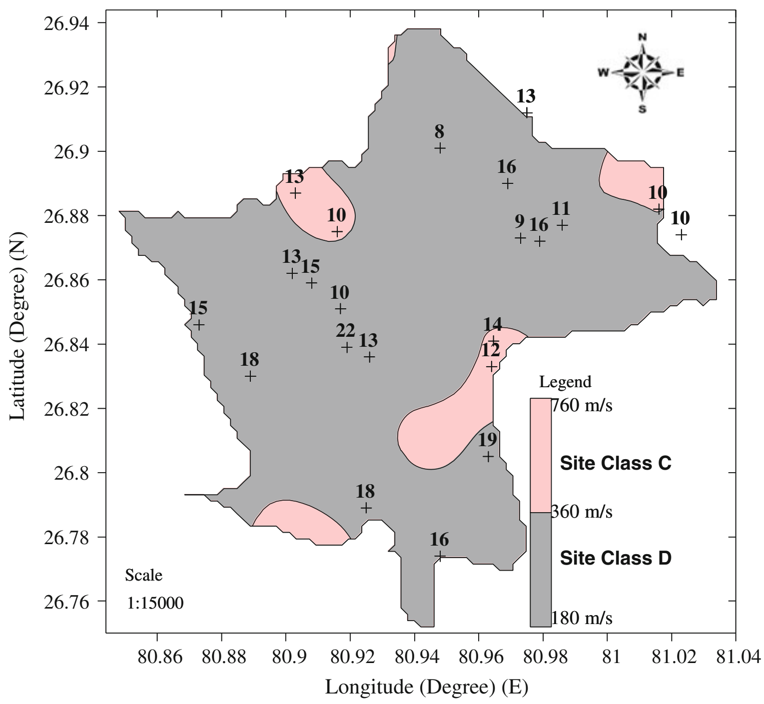


Figure 8
Average 30 m shear wave velocity and N-SPT values as per NEHRP site classification

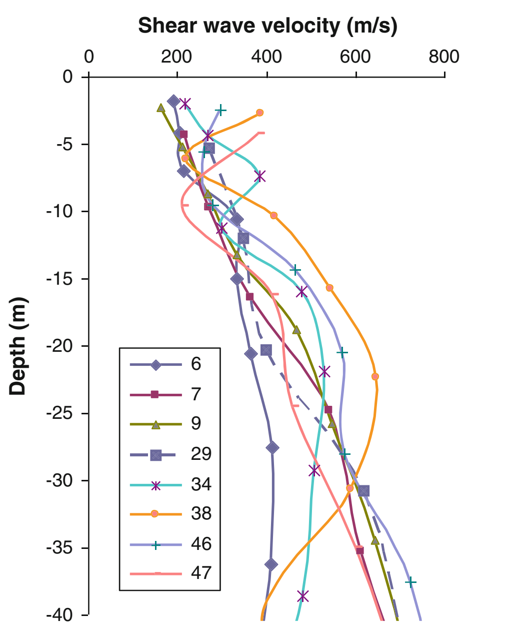


Figure 9
Shear wave velocity profile corresponding to site class C as per NEHRP site classification

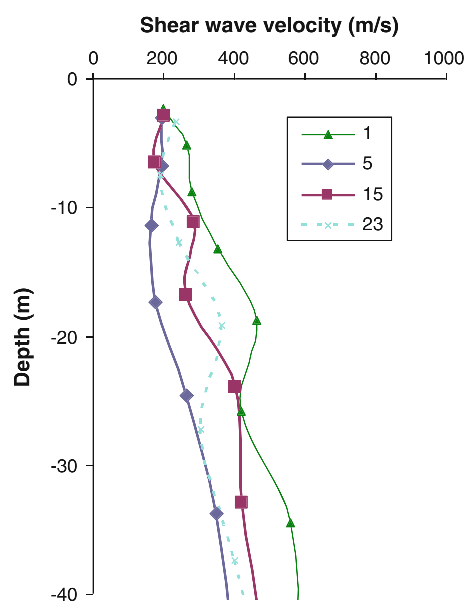


Figure 10
Selected shear wave velocity profile corresponding to site class D

values as per the NEHRP classification system is observed.

Average SWV to a depth where SWV reaches 360 m/s and SPT-N reaches up to 30 for dense soil was estimated and is mapped in Fig. 11. Similarly, average SWV to a depth where SWV reaches 760 m/s and N-SPT up to 50 corresponding to very dense soil was estimated and is mapped in Fig. 12. Figures 11 and 12 show that, for dense soil and very dense soil as per NEHRP classification, the $V_s$ and SPT-N classification do not match. Site classification based on SWV or N-SPT values is widely practiced in many countries. This study, however, shows mismatch of site classes in the Indo-Gangetic Basin based on these two approaches.

## 8. Correlation Between SWV and Measured N-SPT Value

The relation between N-SPT and dynamic soil properties such as SWV is used routinely in earthquake geotechnical engineering. A summary of these N-SPT versus and SWV correlations is given in Table 1. These correlations are soil dependent and region specific. To date, limited attempts have been made to develop such a relation for soil sites in the Indo-Gangetic Basin (IGB). The subsurface lithology and site classification of Lucknow have been discussed in earlier sections. The other objective of this study is to develop a correlation between N-SPT and measured shear wave velocity. In total, 17 relatively closely spaced MASW and SPT tests were used for this study, distributed throughout the study area (Fig. 3). Mostly two types of soils were encountered from borelog reports, namely sandy and clayey soil. Traces of silts were found only at very limited locations, as can be observed from Figs. 2 and 7a, b. Based on the collected sets of SWV and N-SPT values, attempts were made to investigate the correlation between SWV and SPT-N. Such empirical correlation was developed separately for clay, sand, and mixed soil types. The form of the correlation between N-SPT and SWV considered for the regression is as follows:

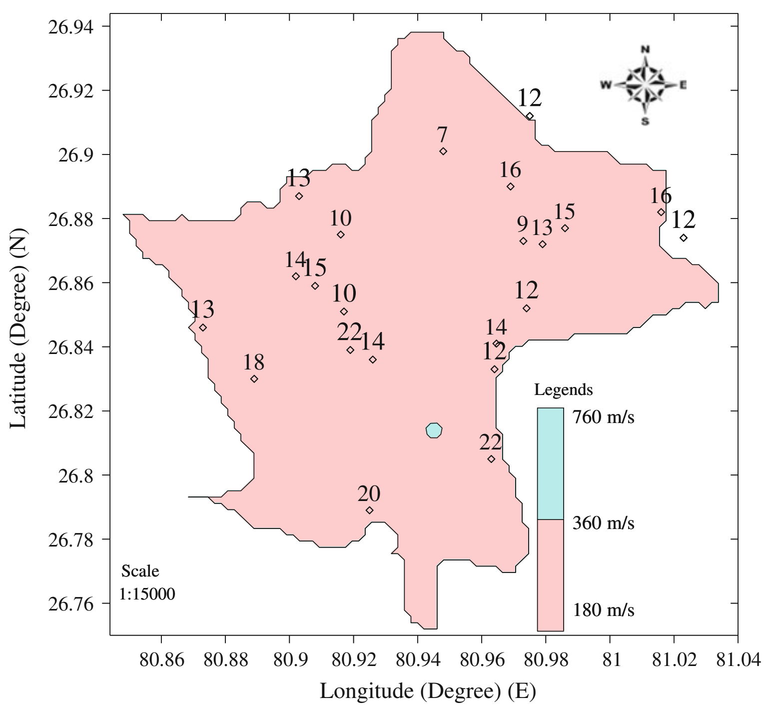


Figure 11
Average shear wave velocity up to 360 m/s and average $N$ values up to $N$ value of 30, corresponding to dense soil

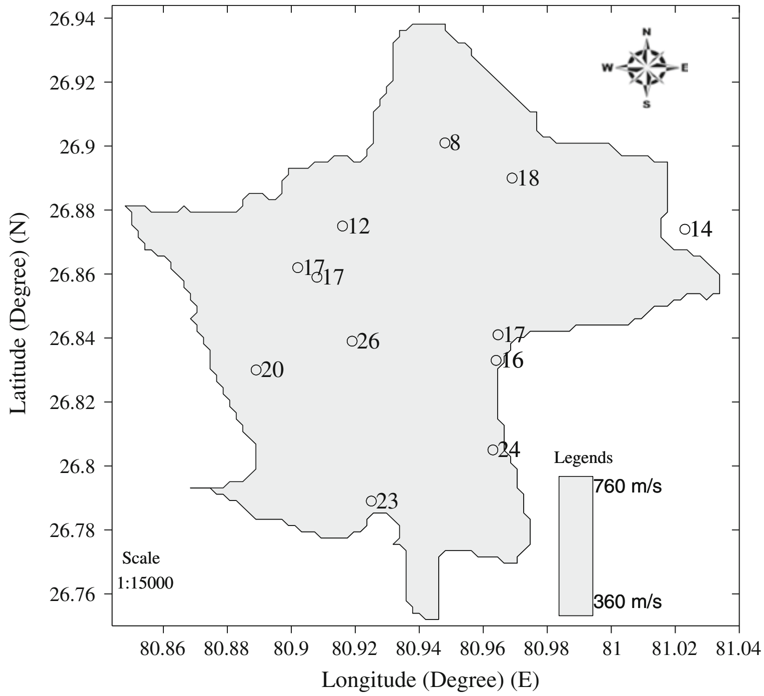


Figure 12
Average shear wave velocity up to 760 m/s and average *N* values up to *N* value of 50

$$V_s = a(N)^b, \quad (5)$$

where *a* and *b* are regression coefficients, being inversely proportional to each other (Ohsaki and Iwasaki, 1973; Imai, 1977; Ohta and Goto, 1978; Imai and Tonouchi, 1982; Iyisan, 1996; Jafari *et al.*, 1997). $V_s$ and *N* are the measured shear wave velocity (SWV) and N-SPT value for the same location. Figure 13a and b show the correlation between SWV and N-SPT for clayey and sandy soil with respective data points. The performance of any regression equation is determined by its root-mean-square (RMS) value. The correlation obtained for clayey soil was $V_s = 106.63(N)^{0.39}$, with $R^2$ of 0.74. For sandy soil, the resulting correlation was $V_s = 60.17(N)^{0.56}$, with $R^2$ of 0.86. These correlations may be useful when soil can be separated based on engineering or geological classification. Even though data are separable based on details of geotechnical investigation, in practice it is difficult to do so because both types of soil are present in each borehole. These correlations may not be user-friendly for field engineering in the absence of a detailed geotechnical report. Thus, to simplify this result, the above two datasets were combined and another correlation proposed, which will be applicable to all soil types in the region. The combined data with the best-fit correlation is shown in Fig. 13c. The proposed correlation for all types of soil is given in Eq. 3 (with $R^2$ value of 0.85):

$$V_s = 68.96(N)^{0.51}. \quad (6)$$

All three correlations are comparable to each other. The $R^2$ value based on the correlation developed for clayey is less than the $R^2$ values for the other two correlations. The $R^2$ value for sand and all soil types are similar. The combined correlation has uncertainty $\sigma_{V_s}$ of 54.06, $\sigma_a$ of 0.0093, and $\sigma_b$ of $1.76 \times 10^{-7}$, where $\sigma_{V_s}$, $\sigma_a$, and $\sigma_b$ are the uncertainties corresponding to $V_s$, *a*, and *b* values, respectively, as given in Eqs. 5 and 6. The ratio of SWV measured from field tests to the predicted $V_s$ is shown in Fig. 14. It can be seen that the data are close to the 1:1 line and lie between the two lines with slopes of 1:0.75 and 1:1.5.

Based on the proposed relation for all types of soils, an attempt was made to identify the lithology

Table 1

*Correlation between SPT-N and $V_s$ values used for the comparison*

| SR. No. | Authors | Existing correlation for all types of soil |
|---|---|---|
| 1 | Ohba and Toriuma (1970) | $V_s = 84N^{0.31}$ |
| 2 | Fujiwara (1972) | $V_s = 92.1N^{0.337}$ |
| 3 | Ohsaki and Iwasaki (1973) | $V_s = 81.4N^{0.39}$ |
| 4 | Imai and Yoshimura (1975) | $V_s = 76N^{0.33}$ |
| 5 | Imai *et al.* (1975) | $V_s = 89.9N^{0.341}$ |
| 6 | Imai (1977) | $V_s = 91N^{0.337}$ |
| 7 | Ohta and Goto (1978) | $V_s = 85.35N^{0.348}$ |
| 8 | JRA-Sand (1980) | $V_s = 80N^{\left(\frac{1}{3}\right)}$ |
| 9 | JRA-Clay (1980) | $V_s = 100N^{\left(\frac{1}{3}\right)}$ |
| 10 | Seed *et al.* (1981) | $V_s = 61.4N^{0.50}$ |
| 11 | Imai and Tonouchi (1982) | $V_s = 97N^{0.314}$ |
| 12 | Athanasopoulos (1995) | $V_s = 107.6N^{0.36}$ |
| 13 | Iyisan (1996) | $V_s = 51.5N^{0.516}$ |
| 14 | Hasancebi and Ulusay (2007) | $V_s = 90N^{0.309}$ |
| 15 | Hanumantharao and Ramana (2008) | $V_s = 82.6N^{0.43}$ |
| 16 | Anbazhagan and Sitharam (2008a) | $V_s = 78N_{60}^{0.4}$ |
| 17 | Uma Maheshwari *et al.* (2010) | $V_s = 95.641N^{0.3013}$ |

considering the predicted SWV values for comparison with the drilled borehole shown in Fig. 6 (B3). N-SPT values were taken from the typical borehole (Fig. 6) and used to estimate SWV values considering the proposed correlation (Eq. 6). The N-SPT value at 2.3 m depth is 7, which gave a predicted SWV of 186.04 m/s and could be classified as stiff soil. This is compared with the measured SWV at the corresponding depth of 225.97 m/s for stiff soil. Similarly, at 17.3 m depth, the predicted SWV value is 309.6 m/s for N-SPT of 19, classified as stiff soil. For the same depth, the measured SWV is 288.2 m/s for stiff soil. N-SPT at 29 m is 26, predicting SWV of 364 m/s, in comparison with a measured SWV value of 391 m/s; both SWV lead to classification as very dense soil. The lithology identified based on the SWV predicted from the correlation is well comparable with the measured SWV lithology. The proposed relation gives a very good indication of lithology, apart from helping to estimate SWV in unknown locations.

## 9. Graphical Validation of the Proposed Equation

The proposed correlations were validated based on the RMS value, which provides only information about the whole set of data used in the analysis. Graphical validations were done on the proposed relation for all types of soil. To validate the new relation, comparisons between observed and predicted data are shown. Graphical methods for residual analysis can be used to compare two sets of values (observed and predicted). In the present work, two graphical methods were used to validate the correlation developed for all soil types.

The first validation uses the normal consistency ratio, $C_d$ (Dikmen, 2009), which is defined as

$$C_d = (V_{sm} - V_{sc})/\text{SPT-N}, \quad (7)$$

where $V_{sm}$ is the SWV measured by MASW, $V_{sc}$ is the SWV calculated from Eq. (6), and SPT-N is the measured $N$ value corresponding to $V_{sm}$. The comparison between the measured and predicted SWV values is shown in Fig. 14. The variation of the normalized consistency ratio $C_d$ as obtained from Eq. (7) with N-SPT is shown in Fig. 15a. It can be observed from Fig. 15 that, for N-SPT till 50, the average value of $C_d$ is close to zero. This indicates that the predicted SWV values are very close to the measured SWV value, thus showing good agreement of the calculated with the actual data. Also at lower N-SPT (N-SPT $< 5$) values, the $V_{sc}$ values are within the error range of 5–10 % with respect to $V_{sm}$.

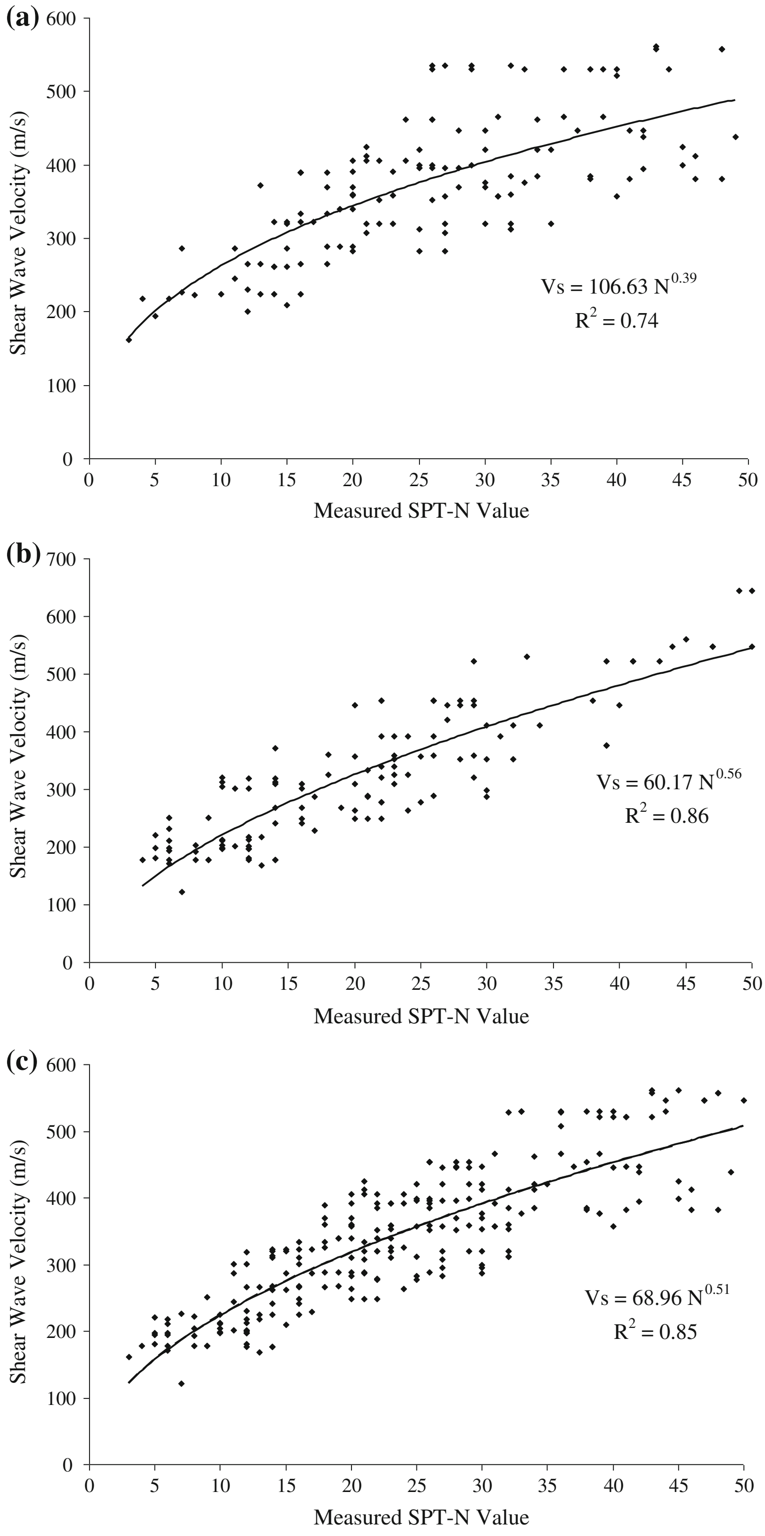


Figure 13

Correlation between N-SPT and $V_s$ values for **a** clayey, **b** sandy, and **c** all soil types

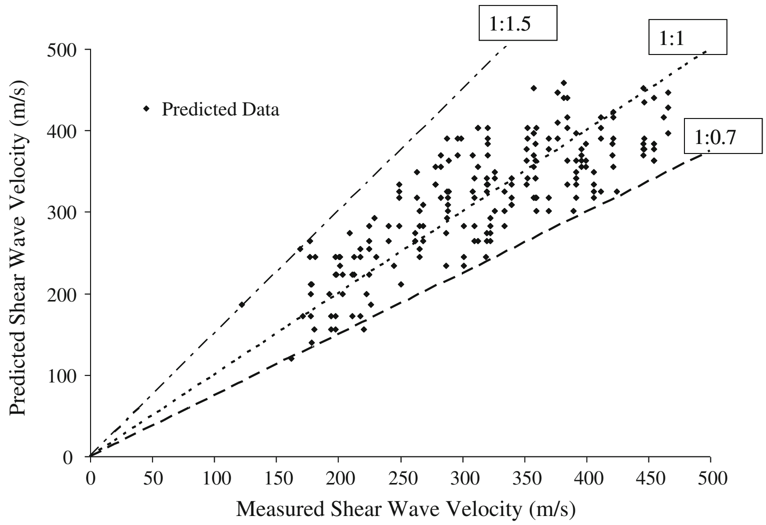


Figure 14
Comparison between measured and predicted $V_s$ values for all types of soils

Secondly, to estimate the capability of the new proposed relationship with recorded field data, the scaled percent error $E_r$ (Dikmen, 2009) was calculated as

$$E_r = 100(V_{sc} - V_{sm})/V_{sc}, \quad (8)$$

where $E_r$ is the scaled percent error, and $V_{sm}$ and $V_{sc}$ are the measured and predicted shear wave velocities. Figure 15b shows the scaled percent error variation for the new relation. It is observed that 80 % of the data were predicted within a 20 % error of margin. The difference in results based on anticipated values and actual values may be due to differences in geotechnical condition, soil characteristics, and stress conditions.

The newly developed correlation can be used for IGB soil deposits or similar soil conditions. There is limited correlation available between N-SPT and SWV for soil sites. Hence, the compatibility of the newly developed correlation with existing and widely used correlations developed for Indian soil and other regions was assessed. The correlation presented by the Japan Road Association (JRA, 1980) is widely used, both in India and worldwide (JRA, 1980). Hanumantharao and Ramana (2008), Uma Maheshwari *et al.* (2010), and Anbazhagan and Sitharam (2008a) have developed correlations between N-SPT and shear wave velocity. The first two relationships by Hanumantharao and Ramana (2008) and Uma Maheshwari *et al.* (2010) were developed using N-SPT values measured in the field. However, the relationship of Anbazhagan and Sitharam (2008a) was developed using corrected N-SPT values. The correlation between the measured and corrected N-SPT values can be found in Anbazhagan and Sitharam (2010). Anbazhagan and Sitharam (2010) showed that measured and corrected N-SPT values gave similar RMS values for residual soil. Figure 16 shows a comparison of the correlation developed in this study with correlations from the Indian researchers listed above and the JRA (1980). It can be noticed in Fig. 16 that the correlation proposed in this study matches very well with all correlations used in India up to N-SPT value of 25. Correlations above N-SPT of 25 are comparable to those reported in Hanumantharao and Ramana (2008). Mismatch of correlations might be due to the depth of N-SPT measured and soil variation in the region. Uma Maheshwari *et al.* (2010), Anbazhagan and Sitharam (2008a, b), and the JRA (1980) used N values from shallower soil deposits (<25 m) compared with this study. Uma Maheshwari *et al.* (2010) and Anbazhagan and Sitharam (2008a, b) used data from residual and older soil deposits from south India, whereas these study data are from younger soil deposits from north India. Correlations developed in this study are comparable for all N-SPT values with the correlation of Hanumantharao and Ramana (2008).

In addition, the relationships in this study are comparable to other global studies. Existing relations for India and other regions of the world are listed in Table 1

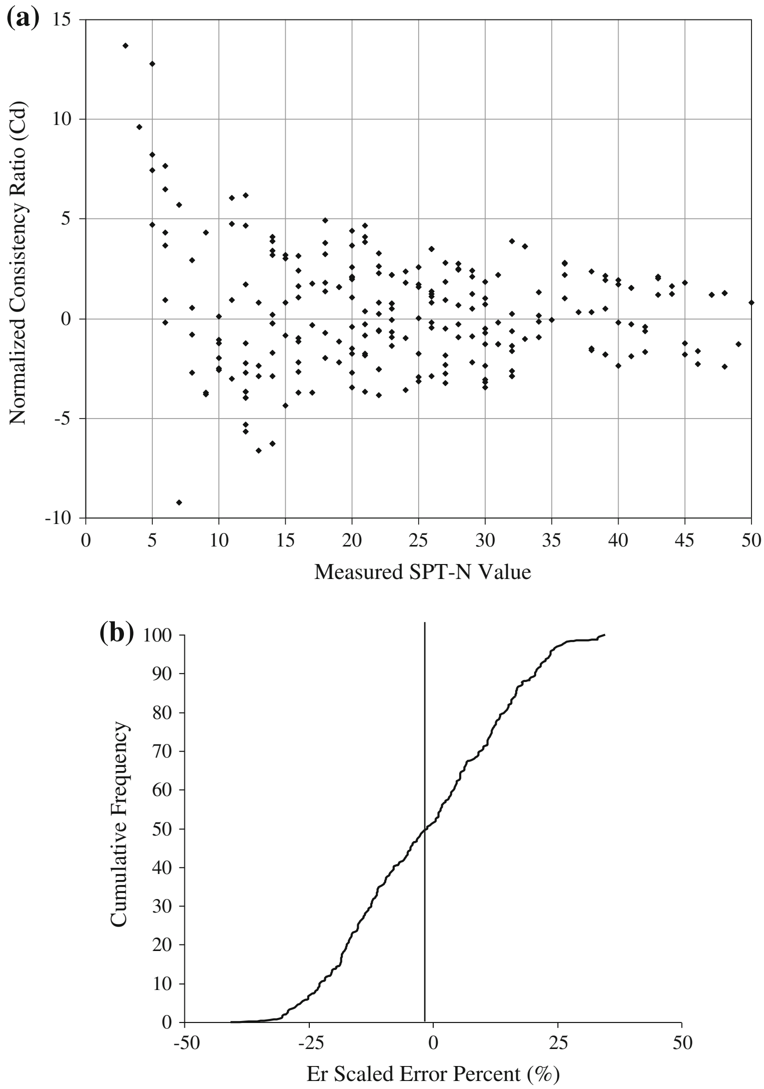


Figure 15
**a** Normalized consistency ratio for the proposed relation for all types of soils. **b** Scaled percent error for proposed correlation

(SR No. 1–17). Figure 17 shows a comparison of worldwide correlations with our proposed relation. It can be observed from Fig. 17 that the new relation is comparable to relations listed in Table 1 and matches well with those of Athanasopoulos (1995) and Seed *et al.* (1981).

## 10. Conclusions

The objective of this paper is to present geological information, site classification and to develop the correlation between $V_s$ versus N-SPT for Lucknow urban center. Detailed subsoil profiles were prepared based on Jal Nigam reports and compared with drilled borehole data from this study and the MASW survey carried out at 47 locations in Lucknow urban center. Shear wave velocities measured in the MASW survey were used for seismic site classification. Soil cross-sections up to 30 m show layers of clay and sand and are comparable to soil profiles reported by the Jal Nigam. Forty-seven SWV and 23 N-SPT profiles were used to develop a seismic site classification of the study area. Based on 30 m average SWV values,

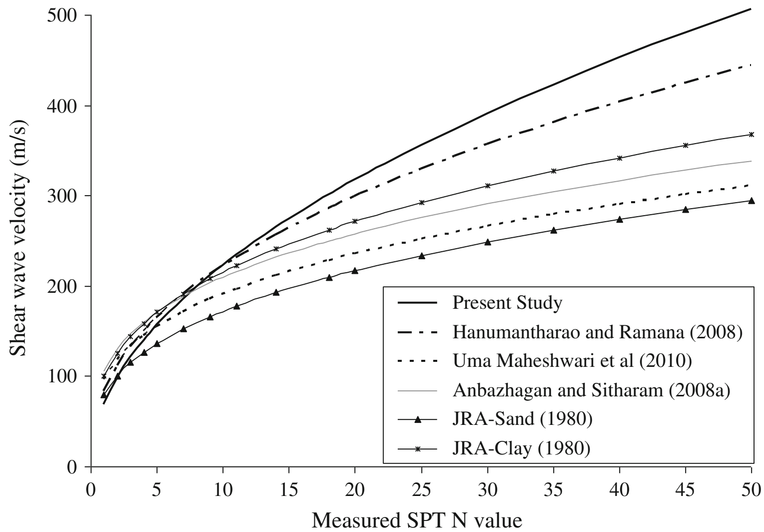


Figure 16
Comparison of proposed relation with other relations used and developed in India

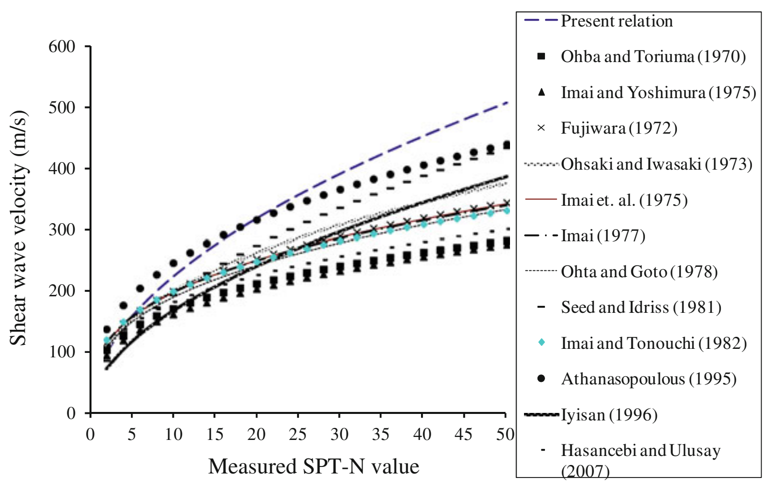


Figure 17
Comparison of proposed relation with worldwide relations for similar condition

most of the city area belongs to site class D with a few locations coming under class C as per the NEHRP site classification. Boreholes with N-SPT values gave site classes E and D. The SPT-based site classification differs from the SWV-based site classification. Of 47 MASW data and 23 boreholes, 17 MASW and boreholes were close to each other, being used to investigate the correlation between SWV and N-SPT values. These data were grouped based on soil type and used to generate the correlation for sandy and clayey soil types. These newly determined relationships were compared with relations available in the literature, showing reasonable agreement for lower *N* values. Also, the relation was validated graphically using the normalized consistency ratio and scaled percent error. The result of the graphical analyses was compared with other relations, showing good agreement. These results can be used for further studies such as site response as will be presented in future publications.

### Acknowledgments

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