Empirical correlation between uncorrected standard penetration resistance \((N)\) and shear wave velocity \((V_s)\) for Kathmandu Valley, Nepal

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ABSTRACT

The indirect method of estimation of \(V_s\) is more important as geophysical tests associated with direct determination of \(V_s\) are not feasible in developing countries like Nepal; on the contrary, standard penetration resistance (SPT-N) measurement is practised widely for building constructions even in residential buildings these days. Good SPT-N database is nowadays available so that eventual development of correlation between these two parameters may provide a strong basis of site characterization as the average shear wave velocity \((V_{s, 30})\) of the upper 30-m soil layer is an important parameter for site characterization. Historically, Kathmandu Valley has experienced anomalous earthquake damage especially at locations with alluvial cover and site characterization is must for improving seismic design considerations. In order to depict a correlation between shear wave velocity and standard penetration resistance available 500 secondary data pairs are used and formulations are obtained considering the geological and geotechnical characteristics. Separate correlations for shear wave velocity as a function of uncorrected standard penetration resistance are developed for all soils, sands and clays separately. Correlation developed for Kathmandu Valley shows significant acquaintance with the existing correlations across the world developed for all soils, sands and clays.

1. Introduction

The seismic shear-wave velocity \((V_s)\) of the upper 30-m soil layer is a governing parameter for ground response and is largely responsible for ground-motion amplification; thus considered as one of the important parameters in present-day quantitative earthquake engineering. Estimation of ground response during earthquake is gaining much attention in recent years (Boore et al. 1993; Anderson et al. 1996; Castro et al. 1997; Building Seismic Safety Council 1998; Park & Elrick 1998; Gautam & Chamlagain 2016; Gautam et al. 2016) and understanding the behavioural anomaly of soil during earthquakes in Kathmandu Valley is being noticed recently. In all of the ground response analyses, strain shear modulus \((G_{\text{max}})\) is used to evaluate the dynamic response of soil. \(G_{\text{max}}\) can be computed with the help of \(V_s\) and soil mass density \((\rho)\) as in expression (1).

\[
G_{\text{max}} = \rho V_s^2
\]
In most of the present-day earthquake engineering practices, $G_{\text{max}}$ is used along with modulus reduction ($G/G_{\text{max}}\gamma$) and damping ($D\gamma$) curves so as to represent the inelastic behaviour of shear strain in dynamic problems. After the 1985 Mexico City and 1989 Loma Prieta, California, earthquakes, studies focused in order to predict the behaviour of soil deposits in terms of local soil amplification, as amplification was the most significant factor behind the localized damage of structures in alluvial deposits (Anderson et al. 1986; Holzer 1994). As a result of this, nowadays many building codes rely on a time averaged $V_S$ while estimating the seismic demand on a structure (e.g. International Conference of Building Officials 1997; Borcherdt 2002).

Until now, many empirical correlations between the geotechnical properties of soil strata and $V_S$ have been generated in order to ease the rapidity of soil behaviour estimation and seismic demand analyses (e.g. Fujiwara 1972; Imai 1977; Ohta et al. 1978; Seed & Idriss 1981; Imai & Tonouchi 1982; Jinan 1987; Lee 1990; Kayabali 1996; Pitilakis et al. 1999; Kiku et al. 2001; Jafari et al. 2002; Andrus et al. 2006; Hasançebi & Ulusay 2007; Hanumantharao & Ramana 2008; Dikmen 2009; Uma Maheshwari et al. 2010; Thaker & Rao 2011; Fabbrocino et al. 2015). Previous contributions as mentioned are accepted for localized regions worldwide in various aspects of geotechnical earthquake engineering and engineering geology for the estimation of soil parameters without laboratory tests. Moreover, the evaluation of foundation stiffness, foundation settlement, seismic site response, site characterization, soil stratigraphy, liquefaction potential, and soil density is also possible to estimate the correlation with the shear wave velocity (Seed & Idriss 1970; Schnabel et al. 1972; Burland 1989; Kramer 1996; Seed et al. 2003; Stewart et al. 2003; Holzer et al. 2005). Recent practices of performing geotechnical observation (SPT-N value) for shallow depth are accomplished in most of the commercial buildings and other government constructions; however, measuring the shear wave velocity is not common in Kathmandu. So, the generation of $V_S - N$ equation is a rational approach for the preliminary understanding of structural and geotechnical earthquake engineering practices. However, this could be more regional and preliminary only as the effects of lithology, depth of soil strata, overburden pressure, geological age of soil deposit and fine contents are not incorporated while performing statistical regressions.

2. Geological and geotechnical characterization of the study area

Kathmandu Valley is an intermountain basin in the Lesser Himalayan zone with relatively younger fluvio-lacustrine deposit of Pliocene to Quaternary age. Non-uniform distribution of sediments (Figure 1) with the basement rocks of Kathmandu Complex (Phulchoki Group and Bhimphedi Group) (Stocklin & Bhattarai 1977) consists the Kathmandu Valley geological composition. The northern and north-eastern parts of the valley consist of fluvio-deltaic or fluvio-lacustrine origin with the dominant sandy facies that is Gokarna Formation and Thimi Formation (Yoshida & Igarashi 1984; Sakai 2001); however, the black clayey central part is mostly composed of Kalimati Formation with the dark grey carbonaceous and diatomaceous beds of the open lacustrine facies (Sakai 2001). Kalimati and Gokarna formations are the most constructed areas in Kathmandu Valley wherein almost all major urban neighbourhoods, administrative areas and critical facilities are concentrated; however, the constructed trend is followed in a similar fashion across the country, this may be the underlying cause of localized and anomalous damage during 1934, 1988 and 2015 earthquakes (Gautam & Chaulagain 2016). Both of the major alluvial formations in Kathmandu Valley consist interbedded sand and silt dominantly and sometimes traces of minor clay contents are available. The average sediment deposit is found up to 500 m depth (Yoshida & Igarashi 1984); the central portion of valley has thicker deposit in comparison to the basin edges. Kathmandu Valley is surrounded by Shivapuri Mountain in the north and Phulchoki in the south with the characteristic bedrock outcropping in the valley. Southern part of Kathmandu Valley is constituted by the Tarebhir Formation, Lukundol Formation and Itaiti Formation (Sakai 2001) from late Pliocene to middle Pleistocene deposits in the hill terraces. Moribayashi and Maruo (1980) estimated the soft soil deposit depth of Kathmandu Valley to be ~650 m through gravity measurements; however, the
variation in the depth of such sediments is non-uniform spatially. Furthermore, Katel et al. (1996) estimated with the help of drilling data of some sites a muddy and sandy sequence up to 300 m depth occurred in Kathmandu Valley. Previous studies in Kathmandu Valley geotechnical observations have presented the domination of silty clay, clayey silt and sand within Kathmandu Valley with the plasticity index ranging from 0 to 23 with high variation of soil amplification (Gautam & Chamlagain 2016; Gautam et al. 2016). Due to poor database and lack of extensive studies regarding dynamic and geotechnical soil characteristics in Kathmandu Valley, adequate information on geotechnical properties and soil non-linearity are not available; however, the study of Gautam and Chamlagain (2016) affirms the interbedded lithostratigraphy of sand and silt with traces of clay sometimes, so these soil types are undoubtedly the representative soil types within Kathmandu Valley alluvium. Available data show that the upper soil stratum consists of primarily the vegetable top soil or filling materials from the dismantled structures or debris from other constructions; this layer is followed by the dark grey sandy silt of low-to-medium plasticity and below this medium plasticity silt to clay are abundant. Some sites of Kathmandu Valley have gravelly soil occurring in the lower strata as well, and such lithological formations are guiding the SPT values in greater extent. The variation of depth and the SPT-N value along with the shear wave velocity measured on site is presented in Figure 2. As general trend of inter-bedding is largely characterized by silt and sand or silt, sand and clay, associated formulations regarding these soil types would be satisfactorily representative.

3. State of the art and formulation of correlation between SPT-N and $V_S$

For a rapid evaluation of shear wave velocities and associated geotechnical parameters, a power equation model $V_S = AN^B$ is practised widely. Wherein $A$ is a constant controlling the amplitude and $B$ has the impact upon relationship curvature. This paper also examines the correlation based
upon the uncorrected SPT-N value and the shear wave velocity irrespective of depth, overburden pressure, geological age, fine content and soil types which may also govern or modify the relationships. Due to the fact that the spatial and vertical lithological variation is not much significant for Kathmandu Valley, as the alluvial deposit consists primarily the low-to-medium plasticity silt to clay, hence preliminary correlation for entire Kathmandu Valley soft soil has been established for the first time based upon PS-logging measurements and SPT-N values, however such correlations may not be ultimate substitution of the in-situ measurements. A set of 500 data pairs with the SPT-N value and $V_s$ are incorporated for regression analysis and the coefficient of determination ($R^2$) is also estimated for each correlation. The PS-logging database for shear wave velocity and uncorrected SPT-N obtained from Kathmandu Valley Earthquake Risk Mitigation Project (JICA 2002) and few other local consultants in personal communication was used to estimate the empirical correlations between shear wave velocity and standard penetration resistance and through extensive literature survey, no any other shear wave velocity measurements database were found to be existed using any other approach like spectral analysis of surface waves (SASW) and so on. The database provided by local agencies in small scales and obtained from JICA (2002) reports was directly in processed form plotted at shear wave velocities and standard penetration resistance values so it is not possible to remark over the methodology, constraints and

Figure 2. (a) Uncorrected SPT-N variation in representative boreholes. (b) Measured shear wave velocity profiles in representative boreholes.
considerations that may have influenced the results. Figure 2(a) represents the profile of SPT values in the upper 30-m soil layer for a typical alluvial location in the study area; similarly, Figure 2(b) depicts the variation of measured shear wave velocity with respect to depth in the same borehole log. Due to interbedded sequence of soil, variation of SPT values has been occurred in wider range even for the upper 30-m soil column. Generally all of the databases considered for this study fall under alluvial formations that is generally characterized by loose sands and silts interbedded and sometimes traces of clay and gravels can be found. Stiff sequences occurring in between the silty and sandy sequences have led the higher SPT and shear wave velocity. Some of the outliers that are drastically deviated from the normal range were discarded for developing correlations. The uncorrected SPT-N values were found to be varying between 3 and 60; albeit the vast majority of the databases are constrained to between 5 and 35. Apart from this, the largest concentration of SPT values can be observed between 5 and 20 (Figure 2(a)). Regarding the shear wave velocities, the majority of data was obtained between 100 and 400 m/s with few cases of 600 m/s as shown in Figure 2(b). An integrated approach as suggested and implemented by Fabbrocino et al. (2015) was used. Integration of geological and geotechnical information and classification of database was performed. It was observed that the interbedded sand and silt was occurring in every location. Due to limited database availability, preliminary correlations are formulated in this paper and can be of interest for exhaustive study in near future.

4. Results and discussion

A simple power regression analysis was carried out to develop the correlation between uncorrected SPT-N value and $V_s$, 500 pairs of representative data from boreholes up to the depth of 30 m were analyzed and the governing equation along with the $R^2$ value is generated for the soft soil deposit of Kathmandu Valley. Separate correlations according to soil type were developed by segregating the database into all soils, silt and sand categories. The overall database was first subjected for the development of empirical correlation for all soils that are prevalent in Kathmandu Valley as shown in Figure 3. The empirical equation for all types of soils is obtained in the form of expression (2) as:

For all soils,

$$V_s = 115.8N^{0.251} \quad (R^2 = 0.623)$$  \hspace{1cm} (2)

Silt is dominantly occurring throughout Kathmandu Valley inter-bedded soft soils; the segregated data pairs as shown in Figure 4 were analyzed to obtain the governing expression as:

![](image3.png)

Figure 3. $V_s$-$N$ correlation for all soils of Kathmandu Valley.
For silt,

\[ V_S = 102.4N^{0.274} \quad (R^2 = 0.355) \]  

(3)

In expression (3), the coefficient of determination is obtained to relatively lower due to limited database and scattered data records. Due to intermixing of different types of soils, usually the soils categorized under similar head are found to be showing different behaviour as reported by Gautam and Chamlagain (2016). Apart from frequent occurrence of silt, Kathmandu Valley soft soil is also characterized by widespread occurrence of sands. Representative equation for sands is obtained in the form of expression (4) as:

For sand,

\[ V_S = 78.7N^{0.352} \quad (R^2 = 0.441) \]  

(4)

The corresponding shear wave velocities and standard penetration resistance values for sand are plotted in Figure 5. A limited number of data were available for formulation of governing equations; it is due to the fact that the majority of soil samples were classified as mixture of sands, silts and clay and sometimes the former two only without traces of clay.

The geophysical tests are seldom performed in Kathmandu Valley due to cost and equipment constraints. The database of PS-logging during the Kathmandu Valley disaster risk management project and few other consultants are utilized to develop preliminary correlations as no records of such correlations are found either for Kathmandu Valley or any other parts of Nepal. For the estimated correlations, the co-efficient of determination \((R^2)\) is found to be relatively low; this may be due to limited data pairs and also might have arisen due to field tests influenced under mechanical and surrounding conditions.

Both NEHRP and IBC accept \(V_{S,30}\) as the fundamental input parameters and representative indicator and Kiku et al. (2001) stated that the upper 30 m of soil stratum is the fundamental factor influencing the ground motions; estimation of \(V_{S,30}\) effectively in low cost is beneficial for designing and implementing the earthquake and structural engineering practices. So this paper attempts to develop some preliminary correlations for various soil conditions that could be helpful in identifying...
the site condition in the aftermath of 2015 Gorkha earthquake for preliminary understanding of behaviour of local soil during construction. Various site classification approaches based on $V_{S30}$ can result exacting variation in associated output parameters though no records of works based on these aspects is obtained for Kathmandu Valley and comparisons are lacking in this study. Due to the lack of developed correlations and field measurement data, comparisons are made with existing empirical correlations worldwide that are presented in Table 1. Consistency of newly developed correlations is depicted through comparative plots in Figures 6, 7 and 8 for respective soil conditions. Newly proposed correlations are found to be well within the correlations developed across the world for similar soil types.

Newly developed correlation for all soils in Kathmandu Valley agrees with the existing correlations worldwide (e.g. Fujiwara 1972; Imai 1977; Ohta et al. 1978; Seed & Idriss 1981; Imai & Tonouchi 1982; Jinan 1987; Lee 1990; Kayabah 1996; Pitilakis et al. 1999; Kiku et al. 2001; Jafari et al. 2002; Andrus et al. 2006; Hasançebi & Ulusay 2007; Hanumantharao & Ramana 2008; Dikmen 2009; Uma Maheshwari et al. 2010; Thaker & Rao 2011) as shown in Figure 6 and lies within the enclosed limit between the correlations developed by Kanai (1966) and Athanasopoulos (1995). Meanwhile least discrepancy is observed with the correlation developed by Uma Maheshwari et al. (2010). Similarly, the correlation developed for silt is also in good agreement with the correlations developed by Lee (1990), Jafari et al. (1997) and Dikmen (2009) enclosed by the equations of Lee (1990) and Dikmen (2009) as in Figure 7. In addition, empirical correlation for sand consents with the existing correlations worldwide (e.g. Shibata 1970; Imai 1977; Seed et al. 1983; Sykora & Stokoe 1983; Okamoto et al. 1989; Lee 1990; Raptakis et al. 1995; Hanumantharao & Ramana 2008; Dikmen 2009) as shown in Figure 8 in satisfactory level. The proposed correlation is bounded by the correlations developed by Okamoto et al. (1989) and Shibata (1970) and closest proximity is observed with the correlation developed by Imai (1977). As these empirically developed correlations have shown good agreement with other studies, for similar soil conditions subsequent application for preliminary understanding may be facilitated in case of Kathmandu Valley with some reservations arising from data limitation.

![Figure 5. $V_s$-SPT correlation for sand of Kathmandu Valley.](image-url)
Kathmandu Valley lacks adequate database to formulate highly representative $V_S - N$ equations. Thus, preliminary correlations for all soils, sands and silts that characterize the dominant soil type of Kathmandu Valley alluvium are developed in this study. Using combined analysis of geological and geotechnical information and as per the lithostratigraphic information, empirical correlations are developed from secondary database. Three equations are developed for all soil conditions, silt and sand separately for the upper 30-m soil column as $V_S = 115.8N^{0.251}$ ($R^2 = 0.623$), $V_S = 102.4N^{0.274}$ ($R^2 = 0.355$) and $V_S = 78.7N^{0.352}$ ($R^2 = 0.441$), respectively, and the developed correlations have shown remarkable acquaintance with existing correlations for respective soil categories. These equations could be instrumental to correlate the widely available SPT-N values in Kathmandu Valley in order to incorporate the seismic design parameters for localized site-specific consideration with the use of SPT-N values on site. Due to the lack of extensive database and

| Researcher(s) | All soils (m/s) | Sand (m/s) | Silt (m/s) | Clay (m/s) |
|---------------|----------------|------------|------------|------------|
| Kanai (1966)* | $V_s = 19 N^{0.6}$ | – | – | – |
| Shibata (1970) | – | $V_i = 31.7 N^{0.54}$ | – | – |
| Imai and Yoshimura (1970)* | $V_s = 76 N^{0.33}$ | – | – | – |
| Ohba and Toriuma (1970)* | $V_s = 84 N^{0.31}$ | – | – | – |
| Ohma et al. (1972) | – | $V_i = 87.2 N^{0.36}$ | – | – |
| Fujiwara (1972) | $V_i = 92.1 N^{0.337}$ | – | – | – |
| Ohzaki and Iwasaki (1973) | $V_i = 81.4 N^{0.39}$ | – | – | – |
| Imai et al. (1975) | $V_i = 89.9 N^{0.341}$ | – | – | – |
| Imai (1977) | $V_i = 91 N^{0.337}$ | $V_i = 80.6 N^{0.331}$ | – | $V_i = 80.2 N^{0.292}$ |
| Ohma et al. (1978) | $V_s = 85.35 N^{0.348}$ | – | – | – |
| Seed and Idriss (1981) | $V_s = 61.4 N^{0.5}$ | – | – | – |
| Imai and Tonouchi (1982) | $V_s = 96.9 N^{0.314}$ | – | – | – |
| Seed et al. (1983) | – | $V_i = 56.4 N^{0.5}$ | – | – |
| Sykora and Stokoe (1983) | – | $V_i = 100.5 N^{0.29}$ | – | – |
| Fumal and Tinsley (1985) | – | $V_i = 152+5.1 N^{0.27}$ | – | – |
| Tonouchi et al. (1983) | $V_i = 97 N^{0.314}$ | – | – | – |
| Jinan (1987) | $V_i = 116.1 (N + 0.3185)^{0.202}$ | – | – | – |
| Okamoto et al. (1989) | – | $V_i = 125 N^{0.3}$ | – | – |
| Lee (1990) | – | $V_i = 57.4 N^{0.49}$ | $V_s = 105.64 N^{0.32}$ | $V_i = 114.43 N^{0.31}$ |
| Athanasopoulos (1995) | $V_i = 107.6 N^{0.36}$ | – | – | – |
| Yokota et al. (1991) | $V_i = 121 N^{0.27}$ | – | – | – |
| Kalteziotis et al. (1992)* | $V_i = 76.2 N^{0.24}$ | – | – | – |
| Pitilakis et al. (1992) | – | $V_i = 162 N^{0.17}$ | – | – |
| Raptakis et al. (1995) | – | $V_i = 106 N^{0.24}$ | – | – |
| Sisman (1995) | $V_i = 32.8 N^{0.51}$ | – | – | – |
| Iyisian (1996) | $V_i = 515 N^{0.516}$ | – | – | – |
| Kayabali (1996) | – | $V_i = 175+(3.75 N)$ | – | – |
| Jafari et al. (1997)* | – | $V_i = 22 N^{0.85}$ | $V_s = 145 (N_{60})^{0.178}$ | – |
| Pitilakis et al. (1999) | – | $V_s = 132 (N_{60})^{0.271}$ | – | – |
| Kiku et al. (2001) | $V_i = 68.3 N^{0.292}$ | – | – | – |
| Jafari et al. (2002) | – | $V_i = 22 N^{0.77}$ | – | $V_i = 27 N^{0.73}$ |
| Hasancebi and Ulusay (2006) | $V_i = 90 N^{0.309}$ | $V_i = 90.82 N^{0.319}$ | – | $V_i = 97.89 N^{0.269}$ |
| Hasancebi and Ulusay (2006) | $V_i = 104.79 (N_{60})^{0.26}$ | $V_i = 131 (N_{60})^{0.205}$ | – | $V_i = 107.63 (N_{60})^{0.237}$ |
| Dikmen (2009) | $V_i = 58 N^{0.39}$ | $V_i = 73 N^{0.33}$ | $V_i = 60 N^{0.36}$ | $V_i = 44 N^{0.48}$ |
| Uma Maheshwari et al. (2010) | $V_i = 95.64 N^{0.301}$ | $V_i = 100.53 N^{0.265}$ | – | $V_i = 89.3 N^{0.358}$ |
| Fauzi et al. (2014) | $V_i = 105.03 N^{0.286}$ | – | – | – |

*Adopted from Akin et al. (2011).
Figure 6. Comparative plot of newly developed and existing correlations for all types of soils.

Figure 7. Comparative plot of newly developed and existing correlations for silts.
measurements based on other techniques of shear profiling, comparison with existing database from Kathmandu Valley is not possible; however, the correlations have shown considerable merit for preliminary understanding of site behaviour under seismic excitation.

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