International Journal of
Geohazards and Environment
http://ijge.camdemia.ca, ijge@camdemia.ca

IJGE 2015 1(1): 42-51

Available at http://ojs.library.dal.ca/ijge

Technical Notes

Evaluation of Shear Wave Velocity Correlations and Development of New Correlation Using Cross-hole Data

Irshad Ahmad[1*], Muhammad Waseem[2], Muhammad Abbas[1], Umair Ayub[1]

[1]Department of Civil Engineering, University of Engineering and Technology, Peshawar, Pakistan
[2]National Center of Excellence in Geology, Peshawar, Pakistan

Abstract: Seismic microzonation studies are being proposed in Pakistan. In addition, a downhole array of accelerometers was planned to be installed in the University of Engineering and Technology, Mardan Campus. Therefore, extensive geotechnical and geophysical tests were conducted. Shear wave velocity (Vs) is a fundamental parameter required for these microzontation studies. It is feasible in terms of cost and space to determine Vs from Standard Penetration Test (SPT) or Cone Penetration Test (CPT) results through empirical correlations. The purpose of this paper is to explore the applicability and predictability of these correlations to the data collected from the area where downhole array is planned. Data from these surveys was used to evaluate relevant correlations selected from literature. Predicted shear wave velocity values from these correlations were compared with measured shear wave velocity values from seismic crosshole tests. Most SPT-Vs correlations evaluated showed low predictability. The SPT-Vs correlation that showed highest degree of fitness to the dataset was the one developed for Lucknow, India, a city with similar geological setting, workmanship and SPT method employed. Site specific SPT-Vs correlation was also proposed. Most of the CPT-Vs correlations evaluated showed considerable predictive capability compared to the SPT-Vs correlations.

Keywords: microzonation, shear wave velocity, cross-hole, geophysical, standard penetration

1 Introduction

Pakistan is an earthquake prone country. It is located at the Himalayan Plate Boundary. Almost two-thirds of the area of the entire country is located on fault lines. Over the past 100 years, this region has been hit by some of the most disastrous earthquakes ever recorded, including the 1935 Quetta earthquake (Moment Magnitude, Mw = 7.5), 1945 Makran Coast earthquake (Mw = 8), 1974 Hunza earthquake (Mw = 6.2) and 2005 Kashmir earthquake (Mw = 7.6). A number microzonation studies are being proposed for different parts of the region. The Vs of soil is an important input into these studies. Vs is a fundamental soil parameter used in soil classification, stratigraphy, determination of liquefaction potential, site response analysis, etc. Vs is preferably measured through in situ seismic non-destructive tests such as crosshole seismic testing, downhole/uphole methods and multi-channel analysis of surface waves (MASW). However, the application of these methods is infeasible due to cost and space constraints. Therefore, empirical correlations have been developed to determine Vs from more simple and common tests such as the SPT and CPT.

SPT is a simple test in geotechnical engineering in which a tube attached to drill rods is driven into the soil down to a distance of 45 cm in three successive increments of 15 cm by a hammer weighing 63.5 kg falling over an anvil through a distance of 76 cm. The number of

* Corresponding Author: Irshad Ahmad, Email: irspk@yahoo.com, Tel: 92-91-9222023

DOI: 10.15273/ijge.2015.01.005

blows recorded is reported as the SPT blow count (SPT-N). A number of design parameters depend on the SPT-N values. Since as early as the 1960's, extensive research has been conducted to develop empirical relationships between Vs and SPT-N and a number of correlations are available in literature (Kanai 1966, Imai 1977, Ohta and Goto 1978, Imai and Tonouchi 1982 Seed et al 1983, Sykora and Stokoe 1983, Kalteziotis et al 1992, Sisman 1995, Pitilakis et al 1999, Kiku et al 2001, Jafari et al 2002, Hasançebi and Ulusay 2007, Dikmen 2009, Uma Maheswari et al 2010, Tsiambaos and Sabatakakis 2011, Anbazhagan et al 2012, Shahzada et al 2012, Fauzi et al 2014). These correlations have been developed for different types of soils. Most of these correlations were developed for uncorrected SPT values.

The Cone Penetration Test (CPT) is another common in situ method employed for accurate determination of soil stratigraphy, soil type, lithologic anamolies and some other soil geotechnical parameters. In the conventional CPT test, a standard instrumented cone is vertically forced into the soil at controlled rate. The tip resistance (qc), sleeve friction (fs) and pore water pressure (u) are recorded. This test gives continuous, reliable and repeatable results. Extensive research, since as early as the 1980's, has been conducted to develop correlations between CPT results and Vs (Baldi et al 1989, Robertson 1990, Hegazy and Mayne 1995, Mayne and Rix 1995, Mayne 2006, Mayne 2007, Andrus et al 2007, Robertson 2009). These correlations have been developed for different types of soils.

Mardan is a central city of the earthquake-prone province of Khyber Pakhtunkhwa in Pakistan. Mardan is classified in seismic zone 2B according to Building Code of Pakistan (Seismic Provisions-2007). Extensive geotechnical and geophysical investigations were carried out as a prerequisite to a comprehensive program of deploying seismic accelerometer arrays in Mardan. Included in these tests were SPT, CPT, seismic crosshole test (CH), MASW, cyclic triaxial tests, resonant column tests, etc. In this study, the data from these investigations was used to evaluate relevant SPT-Vs and CPT-Vs correlations from literature. Vs values measured through CH were used to determine the predictive capability of these correlations. Except for the work of Shahzada et al (2012), little or no research has been done on the subject to develop correlations meeting the geological setting of Pakistan. Shahzada et al (2012) correlated SPT-N values with Vs obtained from MASW. Whereas in this study, SPT-N values were correlated with Vs obtained seismic crosshole test (CH), which is a more reliable test than MASW (Anderson et al 2007). New empirical correlations for SPT-Vs and CPT-Vs have been proposed herein and compared to the selected existing correlations. The degree of fitting of all existing and proposed regression equations was evaluated through statistical analysis.

2 Site Geology and Seismotectonics

Several segments of the Himalayan plate boundary in Pakistan have active faults including the Chaman fault, Kingri Fault, Kalabagh fault, Ornach Nal fault and the Main Mantle Thrust (MMT). The MMT has shown recent activity as breaks in the overlying alluvium and terraces have been observed. The site chosen for this study is located at Mardan. Mardan is one of the major cities of the Khyber Pakhtunkhwa province of Pakistan. Seismotectonic map highlighting the faults in the surrounding areas of Mardan is given in Fig. 1.

Mardan is located in the Peshawar Basin. The Peshawar Basin covers a part of the Himalayan fold-and-thrust belt, it is believed to have been carried passively on the back of low angle detachment faults and thrust sheets, some of which find surface expression in hill ranges to the south of the basin. It is thus classified as a piggyback-type basin. The Peshawar Basin covers a vast area (over 5,500 km^2), having besides Mardan, Charsadda, Noshera and Peshawar as its major cities. It is situated at the southern margin of Himalayas and bounded by the Khyber ranges in the west/northwest, Attock cherat ranges in the South and Swat in the North/Northeast. Quaternary fanglomerates form the basin margins, whereas fluvial micaceous sands, gravels and lacustrine deposits cover its central part. The fluvial deposits have a northern provenance and were probably deposited by the ancestral Kabul and Indus Rivers. However, in the southern part of the basin, fanglomerate and lacustrine deposits have been apparently derived from the Attock-Cherat and adjacent ranges.

Mardan is divided into the north-eastern hilly area and the south-western plain. The northern region is bounded by hills with highest peaks of Pajja and Garo measuring 2056 m and 1816 m high, respectively. The southwestern plain is accepted to have once formed the bed of a lake which was gradually filled up with deposits of rivers falling in from the northwestern hills. Most of the area of the city is waterlogged and underlain by Holocene and Quaternary alluvial deposits. With a population of over 2 million, the city is now developing into an urban center in the province.

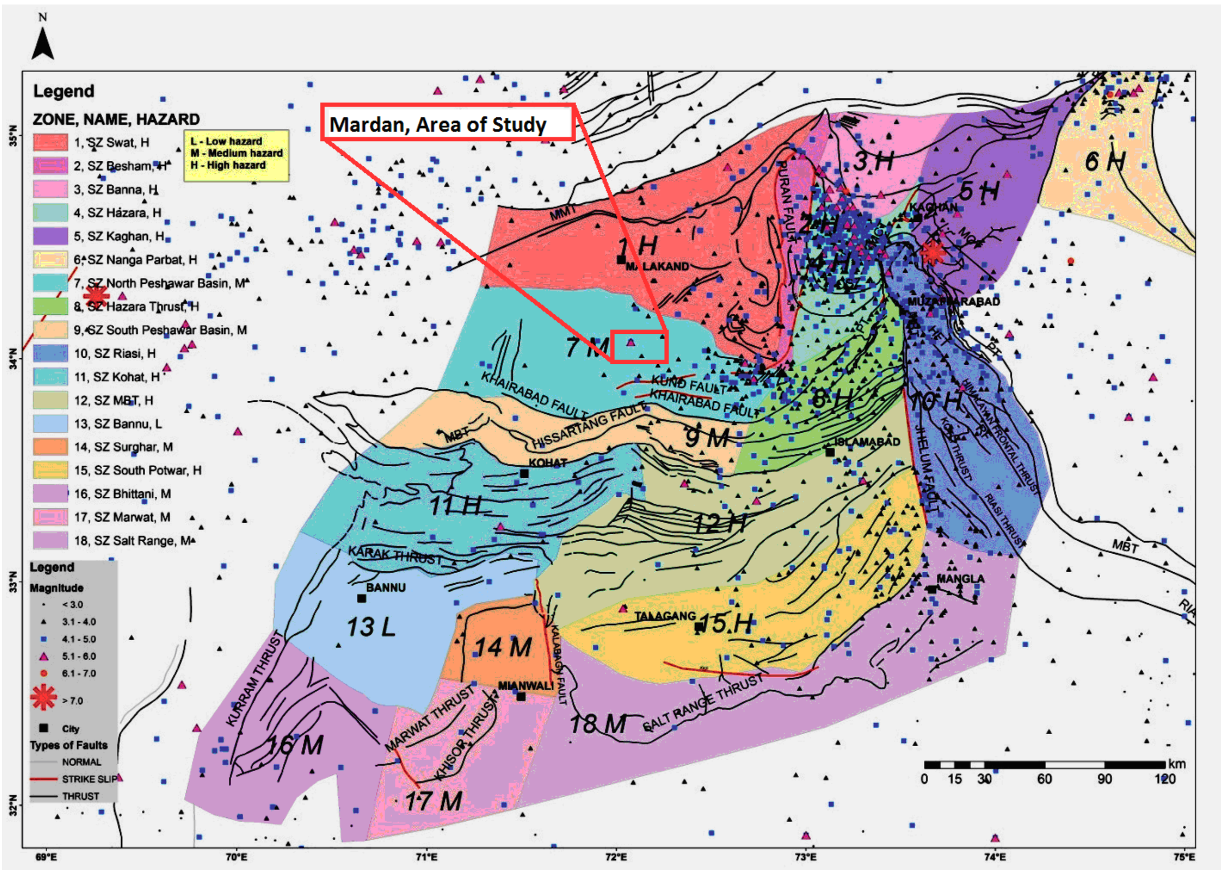

Fig. 1 Seismotectonic zonation map of the NW Himalayan Fold-and-Thrust Belt (MonaLisa et al 2009)

3 In situ tests and subsurface conditions

Three boreholes were drilled in line, each 1 m apart. The central borehole was 100 m deep while the other two were 50 m deep. SPT was conducted in all three boreholes. Donut hammer with a rope and pulley system was used for SPT measurements. A total of 86 SPT measurements were recorded up to a depth of 100 m. In addition, a total of 32 disturbed and 21 undisturbed samples were collected from the boreholes for laboratory testing. A variety of laboratory tests were performed over these samples for the determination of moisture content, Atterberg's limits, specific gravity, consolidation, grain size analysis, etc. To determine the dynamic soil properties, undisturbed samples were used for resonant column and cyclic triaxial tests. Average SPT-N variation with depth up to 50 m in the three boreholes is shown in Fig. 2. CPT measurements were recorded up to a depth of 23 m (Fig. 3). Seismic crosshole test was performed for determining Vs variation within the soil profile along the depth. Measurements were made at every meter up to a depth of 50 m. Variation of measured shear wave velocity along the depth is shown in Fig. 4.

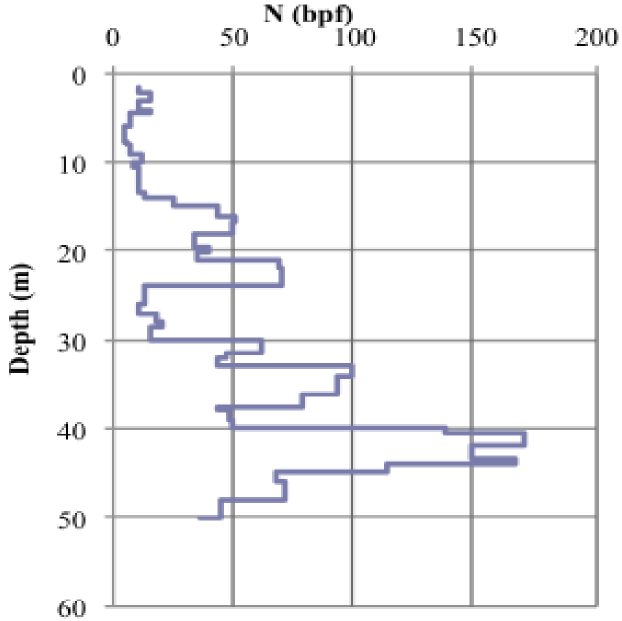

Fig. 2 Variation of average SPT-N value with depth

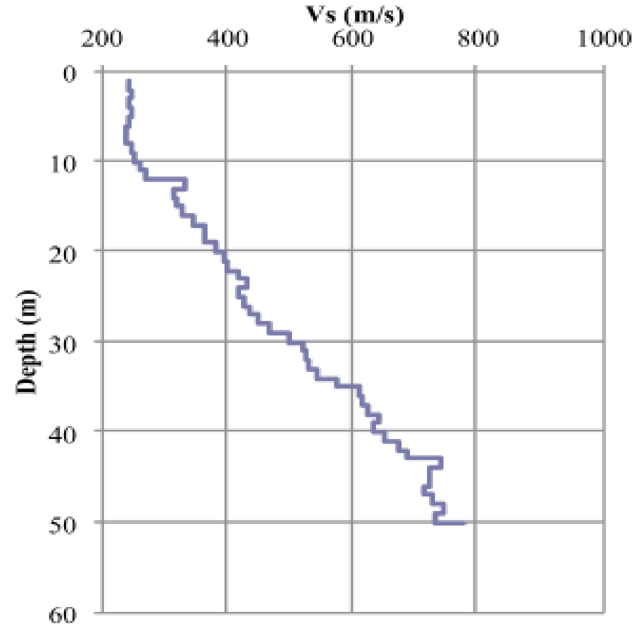

Fig. 4 Variation of Vs measured from CH with depth

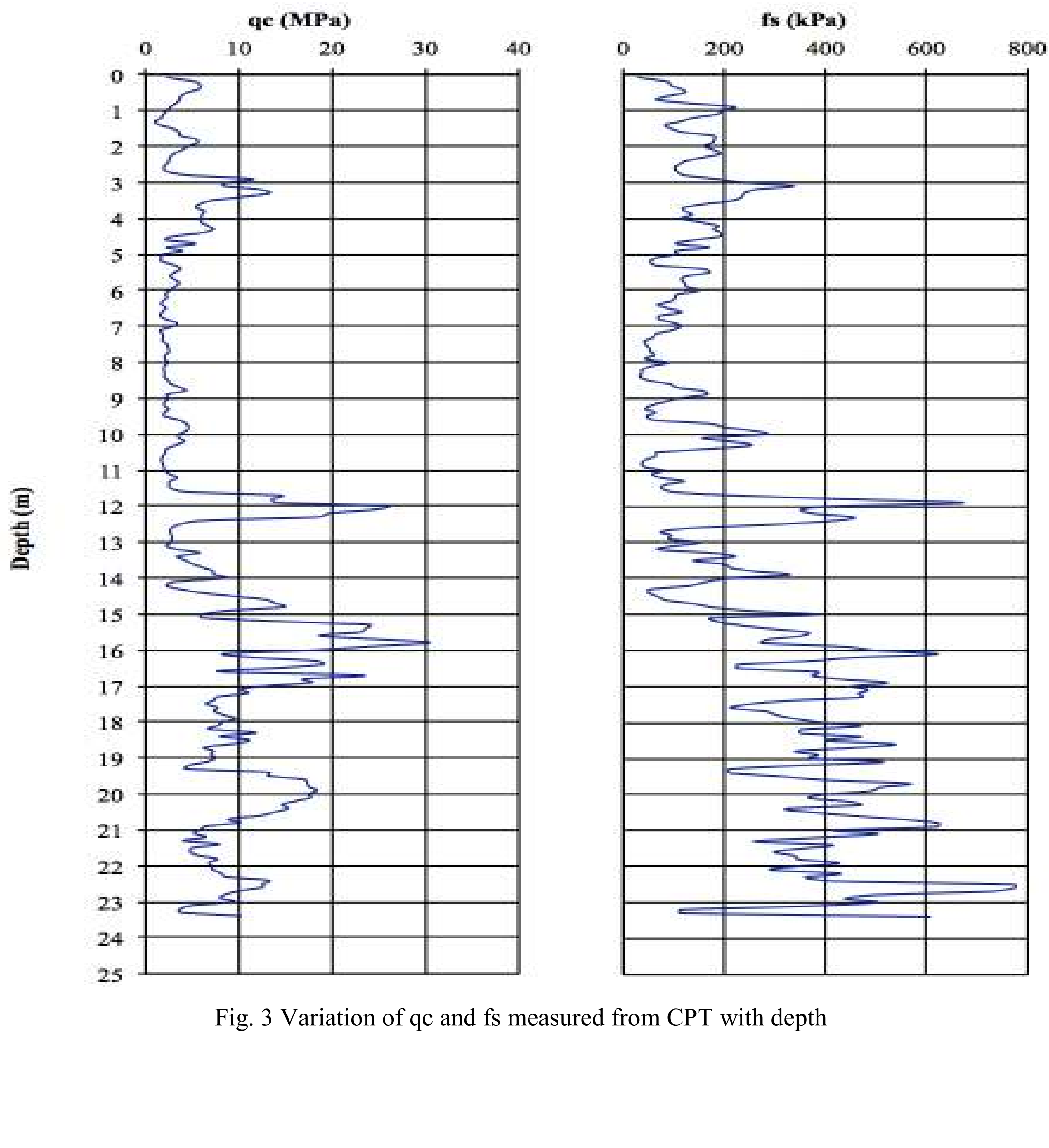

Fig. 3 Variation of qc and fs measured from CPT with depth

The soil profile was highly variable in terms of soil type. Up to a depth of 30 m, intermittent layers of deposits of clay, silty clay and silt were found with low to medium plasticity. Ground water table was encountered at a depth of 4.7 m. From about 30-50 m, soil predominantly composed of layers of stiff silty clay with thin layers of soft silt. The stiff silty clay was grayish brown in color, saturated, contained traces of fine sand and had medium to high plasticity. From 40-45 m, highly stiff soil was encountered containing pieces of mudstone. Minimum plasticity index of 4.2% was observed in the superficial alluvial layers and maximum plasticity index of 15.5% was observed at a depth of 34 m in the stiff silty clay layer. For soil classification, shear wave velocity averaged over 30 m depth (V_{s30}) was found to be equal to 323 m/s. Under the Caltrans/NEHRP soil classification system, the site class for the studied soil profile was D (Stiff Soil).

4 Evaluation of SPT-Vs Correlations

Of many correlations in literature between shear wave velocity and SPT-N, 12 correlations were selected for evaluation. These correlations were selected on the basis of similarities between soil type and age of the study site and those of the original datasets upon which the correlations were based. Details of these correlations are given in Table 1. The SPT and Vs obtained from CH data collected at Mardan in this study was used to evaluate the performance of these existing correlations. All of these correlations were developed using uncorrected SPT-N values.

The scatter of points shown in Fig. 5 indicates the data pairs of uncorrected SPT-N values and measured values of Vs along the depth. Each of the selected correlations was used to predict V_s for every SPT-N value. The measured and predicted values of V_s were used to determine the degree of fitness of each correlation in terms of R-squared value (R^2), root mean square deviation (RMSD) and coefficient of variance of RMSD (CVRMSD). A summary of the selected correlations and their degrees of fitness to the dataset of the study site is given in Table 2. Most of the selected correlations underpredict shear wave velocity for SPT-N values greater than 50. Correlation by Anbazhagan et al (2012) shows the greatest degree of fitness to the dataset with R^2 value of 0.45.

5 Evaluation of CPT-Vs Correlations

Four empirical regression equations correlating CPT results with Vs were selected from literature. The details of these correlations are given in Table 1. The input parameters for predicting Vs were qc, fs and depth (z). The values of Vs predicted from selected correlations were compared with Vs measured values from the study site. Figure 6 shows the plots of measured Vs values and those predicted by the selected correlations. The degree of fitness was determined in terms of R^2, RMSD and CVRMSD. A summary of the selected correlations and their degrees of fitness to the dataset for the study site is given in Table 3. It was observed that equations developed by Mayne (2006) and Piratheepan (2002) showed greatest predictive capability with R^2 values of 0.933 and 0.824 respectively. Piratheepan's (2002) proposed correlations were based on CPT data collected from the United States, Canada and Japan. The correlation was originally developed for Holocene clayey soils and a total of 20 data pairs were used. Mayne (2006) proposed a correlation for a large dataset collected from worldwide sites. The regression equation was developed for all soils using 161 data pairs. Since the existing correlations showed substantial fitness to the dataset used in this study, no new correlations were proposed.

6 Proposed correlation between SPT N and Shear wave velocity

To take into account the effect of indigenous SPT hammers used, workmanship and geology, a dedicated correlation was developed. Sixty-seven data pairs between uncorrected SPT-N values and measured values of Vs were used for developing statistical correlations between the two parameters. Uncorrected SPT-N values were used for the development of this correlation because they have major effect in estimation of Vs (Dikmen 2009). The following two models were selected for developing correlations between SPT-N and V_s:

Table 1 Summary of existing relevant SPT-Vs and CPT-Vs selected for evaluation

S.N.	Authors	Original Equations	Remarks
SPT-Vs Correlations			
1	Uma Maheswari et al (2010)	$Vs= 89.31\ N^{0.358}$	Developed for Cohesive Soils - Vs determined from MASW
2	Dikmen (2009)	$Vs= 44\ N^{0.48}$	Developed for Cohesive Soils - Vs determined from field geoseismic tests
3	Hasancebi and Ulusay (2007)	$Vs=97.89\ N^{0.269}$	Developed for Cohesive Soils - Vs found from field geoseismic tests
4	Jafari et al (2002)	$Vs=27\ N^{0.73}$	Developed for Cohesive Soils- Vs from seismic refraction, downhole and SASW
5	Raptakis et al (1995)	$Vs= 184.2\ N^{0.17}$	Developed for Cohesive Soils using geophysical tests for Vs
6	Kalteziotis et al (1992)	$Vs= 76.6\ N^{0.45}$	Developed for Cohesive using geophysical tests for Vs Soils
7	Lee (1990)	$Vs=114.43\ N^{0.31}$	Developed for Cohesive Soils – Vs from seismic downhole tests
8	Japan Road Association (1980)	$Vs=100\ N^{0.33}$	Developed for Cohesive Soils using geophysical tests for Vs
9	Anbazhagan et al (2012)	$Vs=106.63\ N^{0.39}$	Developed for Cohesive Soils - Modified previous correlations to suit indigenous setting
10	Seed et al (1983)	$Vs= 56.4\ N^{0.5}$	Developed for Cohesionless Soils using geophysical tests for Vs
11	Imai (1977)	$Vs= 102N^{0.242}$	Developed for Cohesive Soils using geophysical tests for Vs
12	Tsiambaos and Sabatakakis (2011)	$Vs= 88.8N^{0.370}$	Developed for Cohesive Soils – Vs from seismic crosshole tests
CPT-Vs Correlations			
1	Hegazy and Mayne (1995)	$Vs=(10.1\log(qc)-11.4)^{1.67}\ (100fs/qc)^{0.3}$	Developed for All Soils- Based on data from 61 sites worldwide
2	Mayne (2006)	$Vs=118.8\log(fs)+18.5$	Developed for All Soils
3	Piratheepan (2002)	$Vs=32.2\ qc^{0.089}\ fs^{0.121}\ D^{0.215}$	Developed for All Soils- Based on data collected from the United States, Canada and Japan
4	Piratheepan (2002)	$Vs=11.9qc^{0.269}\ fc^{0.108}\ D^{0.127}$	Developed for Clay- Based on data collected from the United States, Canada and Japan

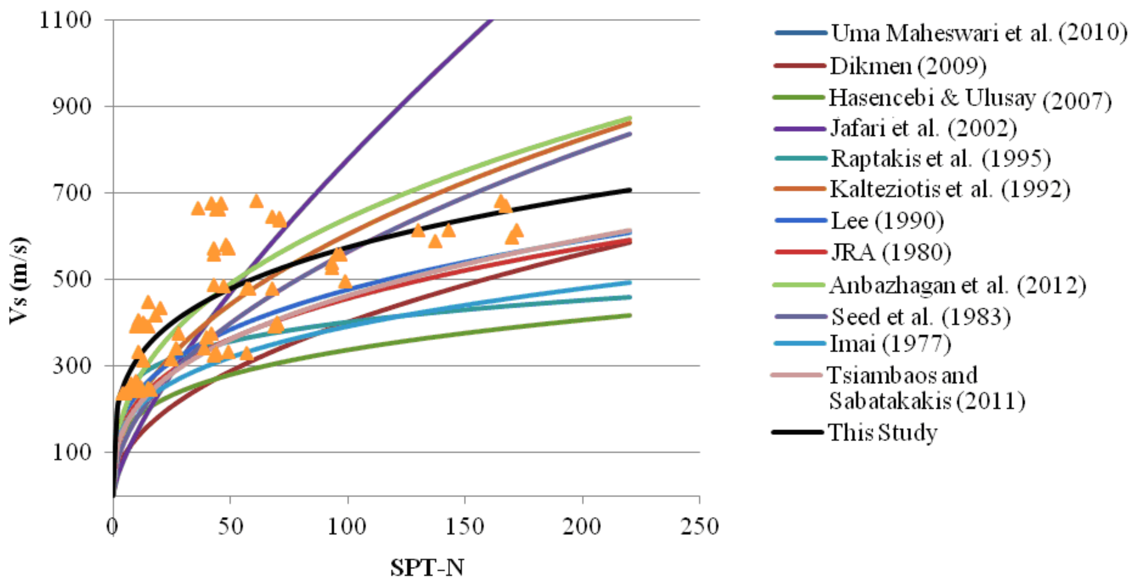

Fig. 5 Comparison of Vs values predicted from SPT-Vs correlations and Vs measured by CH

Table 2 Degree of fitness of evaluated SPT-Vs correlations to the dataset from study site

S.N.	References	Correlation of Vs (m/s)	RMSD	CVRMSD	R^2
1	Uma Maheswari et al (2010)	$Vs= 89.31\ N^{0.358}$	138	0.31	0.13
2	Dikmen (2009)	$Vs= 44\ N^{0.48}$	206	0.47	-0.93
3	Hasancebi and Ulusay (2007)	$Vs=97.89\ N^{0.269}$	212	0.48	-1.05
4	Jafari et al (2002)	$Vs=27\ N^{0.73}$	209	0.47	-0.98
5	Raptakis et al (1995)	$Vs= 184.2\ N^{0.17}$	153	0.35	-0.07
6	Kalteziotis et al (1992)	$Vs= 76.6\ N^{0.45}$	120	0.27	0.34
7	Lee (1990)	$Vs=114.43\ N^{0.31}$	131	0.30	0.21
8	Japan Road Association (1980)	$Vs=100\ N^{0.33}$	146	0.33	0.03
9	Anbazhagan et al (2012)	$Vs=106.63\ N^{0.39}$	110	0.25	0.45
10	Seed et al (1983)	$Vs= 56.4\ N^{0.5}$	139	0.32	0.12
11	Imai (1977)	$Vs= 102N^{0.242}$	179	0.41	-0.46
12	Tsiambaos and Sabatakakis (2011)	$Vs= 88.8N^{0.370}$	138	0.31	0.13

Table 3 Degree of fitness of evaluated CPT-Vs correlations to the dataset from study site

S.N.	Reference	Correlation for Vs (m/s)	RMSD	CVRMSD	R^2
1	Hegazy and Mayne(1995)	$Vs=(10.1\log(qc)-11.4)^{1.67}(100fs/qc)^{0.3}$	69	0.159	0.77
2	Mayne (2006)	$Vs=118.8\log(fs)+18.5$	37	0.086	0.93
3	Piratheepan (2002)	$Vs=32.2\ qc^{0.089}\ fs^{0.121}\ D^{0.215}$	80	0.185	0.69
4	Piratheepan (2002)	$Vs=11.9qc^{0.269}\ fc^{0.108}\ D^{0.127}$	61	0.141	0.82

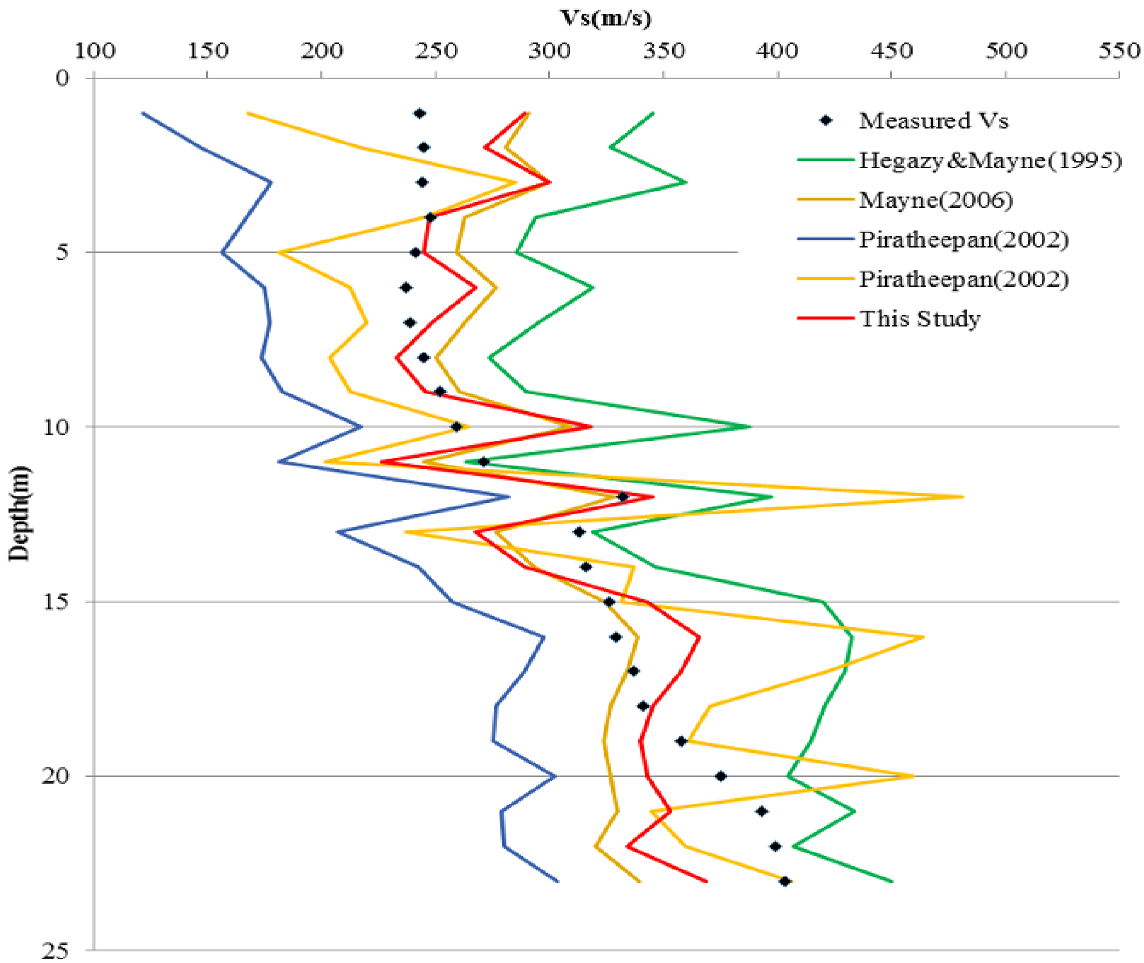

Fig. 6 Comparison of Vs predicted from CPT-Vs correlations and Vs measured by CH

Table 4 Degree of fitness of proposed correlations to the dataset from study site

S.N.	Correlation for Vs (m/s)	RMSD	CVRMSD	R^2
1	$Vs = 82.384N^{0.047}z^{0.475}$	41	0.09	0.92
2	$Vs = 171.02N^{0.263}$	96	0.22	0.58

$$V_s = aN^b z^c \quad (1a)$$

$$V_s = dN^e \quad (2a)$$

where a, b, c and d are coefficients, z is the depth and N is uncorrected SPT-N. Model (1a) was selected to account for the overburden effects and the SPT-N variation. In Fig. 4, it can be seen clearly that the Vs varies almost linearly with depth. Model (2a) was selected because the uncorrected SPT-N values inherently account for overburden effects. Nonlinear regression was performed for the two models using least squares analysis. The equations developed were as follows:

$$V_s = 82.384N^{0.047}z^{0.475} \quad (1b)$$

$$V_s = 171.02N^{0.263} \quad (2b)$$

A summary of the degree of fitness of these equations is given in Table 4. Eq. (1b) is more sensitive to depth (z) than the SPT-N value (N). This high depth-sensitivity is attributed to the almost linear variation of Vs after 10 m.

7 Conclusion

Most of the selected correlations underpredicted the Vs values when SPT-N values exceeded 50. Least predictability was observed for the correlation developed by Hasancebi and Ulusay (2007) with R^2 and CVRMSD equal to -1.05 and 0.48 respectively. This correlation was based on geotechnical and geoseismic tests conducted at a first degree earthquake zone in Turkey. In addition, 8 out of the 12 correlations had R^2 values less than 0.20. This lack of agreement between the predicted and measured values demonstrates the effects of differences in geotechnical characteristics of the study area, geological age, water table effects, over-consolidation effects, etc. The variability could also be due to differences in methods of SPT employed, equipment and workmanship. Correlation developed by Anbazghagan et al (2012) had the greatest degree of fitness to the data pairs of SPT-N and Vs used in this study. This study was performed in Lucknow, India. It is worth noting that India and Pakistan, being neighboring countries, share much of their geological and geotechnical characteristics, SPT hammer characteristics and workmanship. Moreover, the authors classify the sites of their study as C and D based on NEHRP classification system, which is comparable to our site, classified as D under NEHRP soil classification system.

The empirical correlations proposed in this study provide the best fit for the dataset. Eq. (1b) involves a depth factor in addition to the SPT-N parameter. Because the values of Vs from this equation are more sensitive to depth than SPT-N values, this equation will overpredict Vs of any soft soil stratum if encountered at a larger depth. Soft soil layers and their accurate characterization have key role in site response analysis. Therefore, it is recommended that if the SPT-N values increase linearly with depth, Eq. (1b) should be used. However, if SPT-N values do not increase with depth and layers of soft soil are encountered at larger depths, the use of Eq. (2b) is recommended.

All of the CPT-Vs correlations evaluated showed considerable fitness to the dataset of the site of study. Correlation developed by Mayne (2006) showed the greatest predictive capability with an R^2 value of 0.93. Since this equation show sufficient fitness to the dataset, therefore its use is recommended.

References

Anbazhagan, P., A. Parihar and H.N. Rashmi, 2012. Review of correlations between SPT-N and shear modulus: A new correlation applicable to any region. Soil Dynamics and Earthquake Engineering, **36**: 52 - 69. DOI: 10.1016/j.soildyn.2012.01.005.

Anderson, N., T. Thitimakorn, A. Ismail and D. Hoffman, 2007. A comparison of four geophysical methods for determining the shear wave velocity of soils. Environ. Eng. Geosci., **3**(**1**): 11 - 23.

Andrus, R.D., N.P. Mohanan, P. Piratheepan, B.S. Ellis and T.L. Holzer, 2007. Predicting shear-wave velocity from cone penetration resistance. Proc., 4th Inter. Conf. on Earthq. Geotech. Eng., Thessaloniki, Greece.

Baldi, G., R. Bellotti, V.N. Ghionna, M. Jamiolkowski and D.C.F. LoPresti, 1989. Modulus of sands from CPTs and DMTs. Proc., 12th Inter. Conf. Soil Mech. and Foundation Eng., Vol. **1**, Rio de Janeiro, pp: 165 - 170.

Dikmen, Ü., 2009. Statistical correlations of shear wave velocity and penetration resistance for soils. Journal of Geophysics and Engineering, **6**(**1**): 61. DOI: 10.1088/1742-2132/6/1/007.

Fauzi, A., M. Irsyam and U.J. Fauzi, 2014. Empirical correlation of shear wave velocity and N-Spt value for Jakarta, Int. J. of Geomate., **7**(**1**): 980 - 984.

Hasancebi, N. and R. Ulusay, 2007. Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. Bull. Eng. Geology and the Environment, **66**: 203 - 213.

Hegazy, Y.A. and P.W. Mayne, 1995. Statistical correlations between VS and cone penetration data for different soil types. Proc., Inter. Symp. on Cone Penetration Testing, CPT'95, Linkoping, Sweden, Vol. **2**: 173 - 178.

Imai, T., 1977. P-and S-wave velocities of the ground in Japan. Proc. 9th Int. Conf. on Soil Mechanics and Foundation Engineering, 2: 127–132.

Imai, T. and K. Tonouchi, 1982. Correlation of N value with S-wave velocity and shear modulus. Proc., 2nd European Symp. on Penetration Testing, Amsterdam, pp: 67 - 72.

Jafari, M.K., A. Shafiee and A. Ramzkhah, 2002. Dynamic properties of the fine grained soils in south of Tehran. J. Seismo. Earth. Eng., **4** (**1**): 25 - 35.

Japan Road Association, 1980. Specification for highway bridges, Part V, Earthquake Resistant Design.

Kalteziotis, N., N. Sabatakakis and J. Vassiliou, 1992. Evaluation of dynamic characteristics of Greek soil formations. Second Hellenic Conference on Geotechnical Engineering, **2**: 239 - 246.

Kanai, K., 1966. Observation of microtremors, XI: Matsushiro earthquake swarm areas. Bull. Earthq. Res. Inst., Vol. **XLIV**, Part 3, University of Tokyo, Tokyo, Japan.

Kiku, H., N. Yoshida, S. Yasuda, T. Irisawa, H. Nakazawa, Y. Shimizu, A. Ansal and A. Erkan, 2001. In situ penetration tests and soil profiling in Adapazari, Turkey. Proc., ICSMGE/TC4 Satellite Conf. on Lessons Learned from Recent Strong Earthquakes, pp: 259 - 265.

Lee, S.H., 1990. Regression models of shear wave velocities. J. Chin. Inst. Eng., **13**:519-32.

Mayne, P.W., 2006. In situ test calibrations for evaluating soil parameters. Proc., Characterization and Engineering Properties of Natural Soils II, Singapore.

Mayne, P.W., 2007. Cone penetration testing state-of-practice. NCHRP Project 20-05, Topic 37 - 14.

Mayne, P.W. and G.J. Rix, 1995. Correlations between shear wave velocity and cone tip resistance in natural clays. Soils and Foundations, **35**(**2**): 107 - 110.

MonaLisa, M., Q. Jan and A.A. Khwaja, 2009. A preliminary seismotectonic zonation map of the NW Himalayan fold-and-thrust belt, Pakistan for the period 1904-2006. Proc. Pakistan Acad. Sci., **46**(**3**): 175 - 182.

Ohta, Y. and N. Goto, 1978. Empirical shear wave velocity equations in terms of characteristic soil indexes. Earthq. Eng. Struct. Dyn., **6**: 167 - 187.

Piratheepan, P., 2002. Estimating Shear-Wave Velocity from SPT and CPT Data. Master of Science Thesis, Clemson University.

Pitilakis, K., D. Raptakis, K. Lontzetidis, T. Tika-Vassilikou and D. Jongmans, 1999. Geotechnical and geophysical description of Euro-Seistests, using field and laboratory tests and moderate strong ground motions. J. Earthq. Eng., **3**(**3**): 381 - 409.

Raptakis, D.G., S.A.J. Anastasiadis, K.D. Pitilakis and K.S. Lontzetidis, 1995. Shear wave velocities and damping of Greek natural soils. Proc. 10th European Conf. Earthquake Engg., Vienna, pp: 477 - 482.

Robertson, P.K. 1990. Soil classification using the cone penetration test. Canadian Geotech. J., **27**(**1**): 151 - 158.

Robertson, P.K., 2009. Interpretation of cone penetration tests - a unified approach. Canadian Geotech. J., **46**(**11**): 1337 - 1355. DOI: 10.1139/T09-065.

Seed, H.B., I.M. Idriss and I. Arango. 1983. Evaluation of liquefaction potential using field performance data. J. Geotech. Eng., **109**(**3**): 458 - 482.

Shahzada, K., A.N. Khan, S.L. Lin, A. Naseer, M. Javed and M. Fahad, 2012. Seismic hazard assessment of Abbottabad City. Int. J. Earth Sci., **4**(**6**): 212 - 215.

Sisman, H., 1995. An Investigation on Relationships between Shear Wave Velocity, and SPT and Pressuremeter Test Results. Master of Science Thesis, Ankara University, Turkey.

Sykora D.E. and Stokoe K.H., 1983. Correlations of in-situ measurements in sands of shear wave velocity. Soil Dyn. Earthq. Eng., **20**: 125 - 136.

Tsiambaos G. and N. Sabatakakis, 2011. Empirical estimation of shear wave velocity from in situ tests on soil formations in Greece. Bull. Eng. Geol. Environ., **70**: 291 - 297. DOI: 10.1007/s10064-010-0324-9.

Uma Maheswari R., A. Boominathan and G.R. Dodagoudar, 2010. Use of surface waves in statistical correlations of shear wave velocity and penetration resistance of Chennai soils. Geotech. Geol. Eng., **28**(**2**): 119 - 137. DOI: 10.1007/s10706-009-9285-9