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Correlation between shear wave velocity and standard penetration test for Nowshahr and Chalus, Iran

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Abstract

Estimation of ground response during earthquake is gaining much attention in recent years. One of the most important parameters needed to achieve this goal is the shear wave velocity and its related parameters in the surface layers obtained by seismic geophysical tests in place or by laboratory measurements on intact soil samples. Field measurement of such parameter is accurate, but expensive as well as time consuming. Therefore, the need to estimate shear wave velocity using other soil parameters is justified. For example, the numbers of blows (N) from standard penetration test (SPT) are readily available for many sites where geotechnical investigations are carried out. This paper presents a development of reliable correlation between Vs measured by using other soil parameters such as density and shear modulus of soil and N measured using SPT at various sites in Chalus and Nowshahr regions in Mazandaran Province. For this purpose, the results of standard penetration tests conducted in 31 different sites in Chalus and Nowshahr areas were used. Correlation relations were obtained separately for all soils, cohesive and non-cohesive soils. The relationships obtained are within the range of those obtained worldwide for other sites and are comparable to them. Moreover, present correlations, having regression coefficients (R^2) almost 0.92, indicated good prediction capability. The proposed relations obtained are useful for assessment of seismic microzoning of the region.

Keywords: Site effect, shear wave velocity, standard penetration test, Iran

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1 Introduction

Understanding the details of subsurface characteristics and geology stratification is essential to forecast future earthquake (Marto et al., 2013). Local site conditions describe the materials that lie directly beneath the site from the surface to bedrock. The characteristics of the movement due to the occurrence of an earthquake in a site (site effect) are significantly affected by the presence of soil sediments. These characteristics of the ground motion depend on the velocity of the shear wave (Vs). Shear wave velocity is one of the dynamic properties of the soil which can be evaluated as an indicator of the dynamic behavior of the soil. For this reason, determination of soil characteristics constitutes one of the most important aspects of geotechnical microzonation and their values are obtained by directly measuring it in the desert by geophysical methods such as down hole, cross hole, surface wave analysis (SASW) and boundary fracture. Determining the velocity of the soil shear wave by the aforementioned methods, although accurate, is often expensive and may not be economically justified in some projects. In addition, it is not possible to perform these tests on all sites. One of the methods of estimating shear wave velocity indirectly is based on the results of the standard penetration test. For this purpose, the correlation obtained from the standard penetration test results with shear wave velocity is used because penetration numbers (N_{SPT}) from standard penetration tests (SPT) are readily available for many sites, where geotechnical investigations have been or are being conducted. The standard penetration test is one of the oldest and currently, most useful field tests for estimating soil engineering parameters, which were obtained in this research according to Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils (ASTM D1586, 2011).

So far, various empirical relationships between shear wave velocity and standard penetration test results have been presented based on the soil type by various geotechnicians around the world such as Ohba and Toriumi (1970), Imai (1977), and Ohta and Goto (1978) in Japan, Seed and Idriss (1981) in America and Raptakis et al. (1995) in India. In Iran, Jafari et al. (2002) obtained an experimental relationship between N and Vs for all types of soils in the south of Tehran by examining the dynamic properties of various soils. Also, Esfahanizadeh et al. (2015) obtained a correlation between standard penetration test and shear wave velocity for Caspian Sea coasts. In another study, Fatehnia et al. (2015) introduced an experimental relationship between N and Vs for sandy and clay soils in Florida. Kirar et al. (2016) obtained the relationship between shear wave velocity and standard penetration number for three category soils in Roorkee region in India using seismic data and information obtained from geotechnical studies.

Farrokhzad and Choobesti (2016) obtained the correlation between shear wave velocity and standard penetration test for all types of soils (cohesive and non-cohesive) in Babol, Iran. Gautam (2017) determined empirical correlation between uncorrected standard penetration resistance (N) and shear wave velocity (V_S) for all soils, sands and clays separately for Kathmandu Valley, in Nepal. In new research, Ashikuzzaman et al. (2021) developed correlation between shear wave velocity and standard penetration value for Rajshahi District in Bangladesh for all types of soils. The empirical relationship between these two parameters is a function of soil type, density, soil moisture percentage, age and geological history, fine grain percentage, quantity of tests, method of testing and equipment used. Table 1 shows a number of correlations obtained between V_S and N_{SPT}. The difference in the shear wave velocity measurement method is one of the reasons for the differences in existing relationships.

Table 1. Correlation between standard penetration number $(N_1)_{60}$ and V_S (m/s).

No.	Researcher	Soil type	V_S (m/s)
1	Shibata (1970)	Sand	$Vs = 32N^{0.5}$
2	Ohba and Toriumi (1970)	All	$Vs = 84N^{0.31}$
3	Fujiwara (1972)	All	$Vs = 92.1N^{0.337}$
4	Ohta et al. (1972)	Sand	$V_S = 87N^{0.36}$
5	Ohsaki and Iwasaki (1973)	Cohesionless All	$Vs = 59.4N^{0.47}$ $Vs = 81.4N^{0.39}$
6	Imai and Yoshimura (1976)	All	$Vs = 76N^{0.33}$
7	Imai (1977)	Sand All Clay	$Vs = 80.6N^{0.331}$ $Vs = 91N^{0.337}$ $Vs = 102N^{0.292}$
8	Ohta and Goto (1978)	All Sand	$Vs = 85.35N^{0.348}$ $Vs = 88N^{0.34}$
9	Seed and Idriss (1981)	All	$Vs = 61.4N^{0.5}$
10	Seed et al. (1983)	Sand	$Vs = 56.4N^{0.5}$
11	Sykora and Stokoe (1983)	Sand	$Vs = 100.5N^{0.29}$
12	Lee (1990)	Sand Clay Silt	$Vs = 57.4N^{0.49}$ $Vs = 114N^{0.31}$ $V_S = 106N^{0.32}$
13	Raptakis et al. (1995)	Sand Clay	$Vs = 100N^{0.24}$ $Vs = 184.2N^{0.17}$
14	Sisman (1995)	All	$Vs = 32.8N^{0.51}$
15	Jafari (1997)	All	$V_S = 22N^{0.85}$
16	Kiku et al. (2001)	All	$Vs = 68.3N^{0.292}$
17	Jafari et al. (2002)	All Clay (Tehran) Fine Grains (Tehran)	$Vs = 22N^{0.85}$ $V_S = 27N^{0.73}$ $V_S = 19N^{0.85}$
18	Hasancebi and Ulusay (2007)	All Clay Sand	$Vs = 90N^{0.309}$ $Vs = 97.89N^{0.269}$ $Vs = 90.82N^{0.319}$
19	Hanumantharao and Ramana (2008)	All Sand	$Vs = 82.6N^{0.43}$ $Vs = 79N^{0.434}$
20	Lee and Tsai (2008)	All Cohesionless Cohesive	$Vs = 137.153N^{0.229}$ $Vs = 98.07N^{0.305}$ $Vs = 163.15N^{0.192}$
21	Dikmen (2009)	All Cohesionless Cohesive	$Vs = 58N^{0.39}$ $Vs = 73N^{0.33}$ $Vs = 44N^{0.48}$
22	Uma Maheswari et al. (2010)	All Sand Clay	$Vs = 95.64N^{0.301}$ $Vs = 100.53N^{0.265}$ $Vs = 89.31N^{0.358}$
23	Tsiambaos and Sabatakakis (2011)	All Sand Clay	$Vs = 105.7N^{0.327}$ $Vs = 79.7N^{0.365}$ $Vs = 88.8N^{0.370}$
24	Anbazhagan et al. (2012)	All Cohesionless Clay	$Vs = 68.96N^{0.51}$ $Vs = 60.17N^{0.56}$ $Vs = 106.63N^{0.39}$

25	Tavakoli et al. (2014)	All	$V_S = 49.59N^{0.512}$
26	Esfehanizadeh et al. (2015)	Sand	$V_S = 107.2N^{0.34}$
27	Kirar et al. (2016)	All Sand Clay	$V_S = 99.5N^{0.345}$ $V_S = 100.3N^{0.338}$ $V_S = 94.4N^{0.379}$
28	Farrokhzad and Choobbasti (2016)	Clay & Plastic Silt Sand & non-Plastic Silt All	$V_S = 70.424\ N^{0.514}$ $V_S = 83.226N^{0.457}$ $V_S = 73.808N^{0.498}$
29	Ashikuzzaman et al. (2021)	All Sands Calys Silts	$V_S = 72.202N^{0.3779}$ $V_S = 74.446N^{0.3979}$ $V_S = 85.558N^{0.362}$ $V_S = 69.644N^{0.4956}$

It should be noted that the relationships presented in Table 1 are without considering the percentage of fine grain and depth.

In investigating the experimental relationships listed in Table 1, the following points are important:

1- The relations obtained have a relatively large dispersion for a type of soil, so that for a fixed number N, the values of V_S using different relations differ by almost two times.

2- The general mathematical equation that governs the above relationships is $y=ab^x$, which seems to be the most suitable for expressing the correlation between V_S and N_{SPT}.

In this study, an attempt has been made to develop a reliable correlation between Vs and N_{SPT} for soils of Chalus and Nowshahr regions. Shear wave velocity values are estimated using dynamic properties of soil such as density and shear modulus of soil based on information from reports collected by soil mechanics laboratories within Iran.

2 Study area

2-1 Geographical location and climatic characteristics of Chalus and Nowshahr

The studied area is located at longitudes 50°55'E to 51°45'E and latitudes 36°9'N to 36°41'N. The elevation of Nowshahr is zero from the sea level, while it is 29 meters on average for Chalus (It varies from zero, in Radio Darya, to more than 29 meters in the higher parts of the city). In terms of climate, it has sub-Mediterranean climate. Rainfall occurs in all seasons of the year, but its intensity is greater in autumn and decreases to its lowest value in summer. Figure 1 shows the aerial map of the studied area.

2-2 Geomorphology, geology and seismotectonic of the studied area

In the geological map of Chalus and Nowshahr, from north to south, three completely different faces can be seen: 1) the Caspian Sea, 2) alluvial plains and 3) the southern highlands. In Chalus region, the southern highlands, most of faces are made of rocks and sedimentary and volcanic deposits while in Nowshahr region, the exposed rocks are all sedimentary. In both areas, the rocks include stratigraphic series from Permian to Quaternary, with the exception of a few absences of sedimentation (Vahdati Daneshmand et al., 2001; Gharib et al., 2004). The studied area is part of Alborz tectonic seismic state (Mirzaei et al., 1998). The Alborz mountain range in this region has created geomorphological forms that follow the main structures of the region. The Alborz Mountains in northern Iran is considered

Figure 1. Aerial map of Nowshahr and Chalus region.

to be part of the early Paleozoic Gondwanan passive continental margin (Hessami, 2021). Active deformation in the Alborz Mountains is due to the convergence between Central Iran and Eurasia which occurs at a rate of about 5 mm/yr (Vernant et al., 2004). Deformation in the Alborz Mountains is mainly due to the left lateral strike slip faults and a series of longitudinal zones of folding with thrusts that are primary dipping south on the northern side of the mountains while dipping north on the southern side (Hessami, 2021) and with steep slopes formed by the main thrust faults from the north (such as the Caspian fault and the North Alborz fault) and from the south (such as the North Tehran Fault, North Qazvin Fault, Mosha Fault, Khazar Fault and Kojor Fault) are demarcated (Tatar et al., 2010). The Caspian Fault more or less separates the southern foothills and highlands from the northern plains.

Over the past years, Alborz zone has seen many earthquakes. According to the tectonic seismic map of Iran (Hessami et al., 2003), earthquakes are shallow in Alborz. There are also some intermediate types, and on top of that, Eastern Alborz is more seismic than Western Alborz (Aghanabati, 2004) . Figure 2 shows the seismicity of the studied area.

Among the important earthquakes that occurred in Alborz region, we can mention the 1809 Amol earthquake with a magnitude of $M_S = 6.5$, the 1962 earthquake of Bouin Zahra with a magnitude of $M_S = 7.2$, the 1990 Manjil-Rodbar earthquake with a magnitude of $M_S = 7.4$ and the 2004 Firozabad-Kojur earthquake with a magnitude of $M_S = 6.3$.

3 Determining the correlation of shear wave speed (V_S) and standard penetration number ($N_{1(60)}$)

3-1 Geotechnical investigation

The data used in this study were collected samples (more than 130 samples) from 31 sites in different parts of Chalus and Nowshahr cities resulting from standard penetration test (SPT). The total number of boreholes was 31, of which 15 boreholes were located in Chalus and 16 boreholes were located in Nowshahr. But due to incomplete geotechnical information of some boreholes, only 14 boreholes were used. Table 2 shows the number of boreholes and their depths from ground surface which used in this study. Figure 2 shows the location of all boreholes and boreholes used in this study.

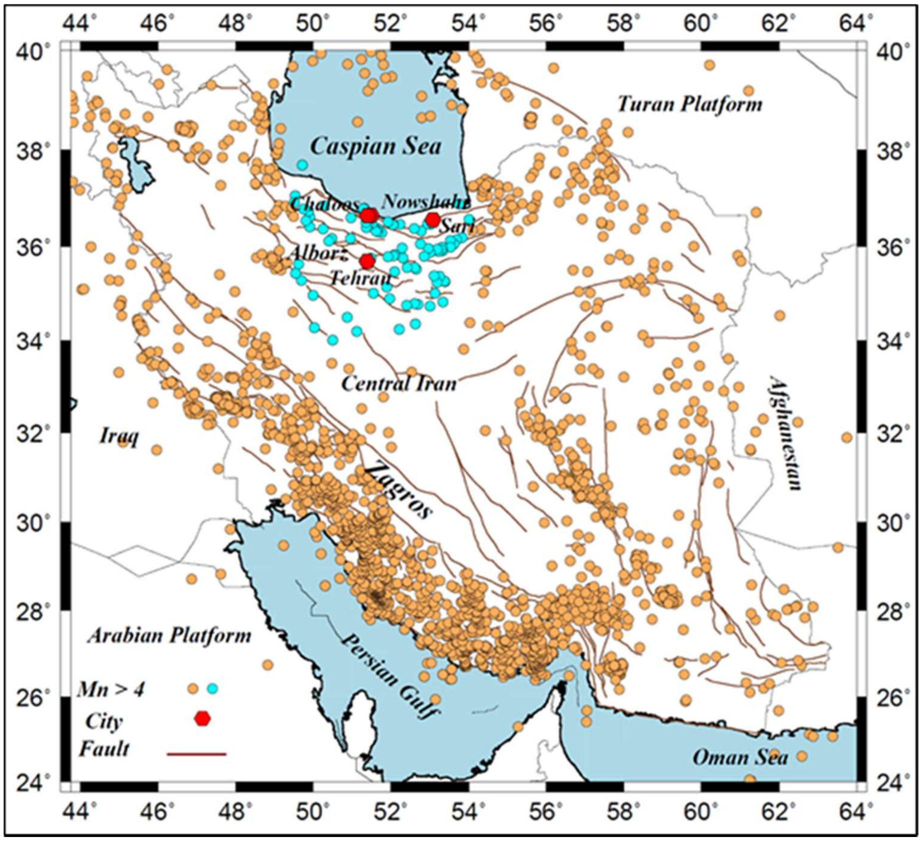


Figure 2. The seismicity of the studied area (from 1996 to 2019 with a magnitude greater than 4 on the Nutley scale) is shown in comparison with the rest of Iran. The data have been recorded by the seismic networks of the Institute of Geophysics, University of Tehran. The solid turquoise and light brown circles show the epicenters of the earthquakes in the Central Alborz region and the rest of Iran, respectively.

Table 2. The depth of boreholes used in this study.

Number of boreholes	Depth from ground surface (m)
4	1-12
2	1-15
2	2-16
2	1-2
1	1.5-18
1	4-20
1	1-3
1	1-15.5

Soil samples collected from different depths of boreholes drilled in the soil mechanics laboratory were examined and their geotechnical parameters such as specific gravity, density, moisture percentage, modulus of elasticity and $(N_1)_{60}$ were obtained. The samples collected from different boreholes include clay, silt, sand and gravel.

Table 3 shows the classification of the types of soil in the used boreholes. The map of water table in Chalus and Nowshahr regions provided by the water affairs department of Chalus and Nowshahr region in 1399-1400 is shown in Figure 3. Based on the Figure 3, we can see that the water table in Chalus (1.51 to 12.58 meters) is lower than Nowshahr (0.85 to 1.5 meters).

Table 3. Classification of layers.

Number of samples	Type of soil		Classification based on size
1	CH	Clay	fine soil
18	CL		
2	MH	Silt	
17	ML		
6	SC	Sand	coarse soil
8	SM		
3	SP		
2	SP-SM		
25	GM	Gravel	
1	GP		
3	GP-GC		
2	GP-CM		

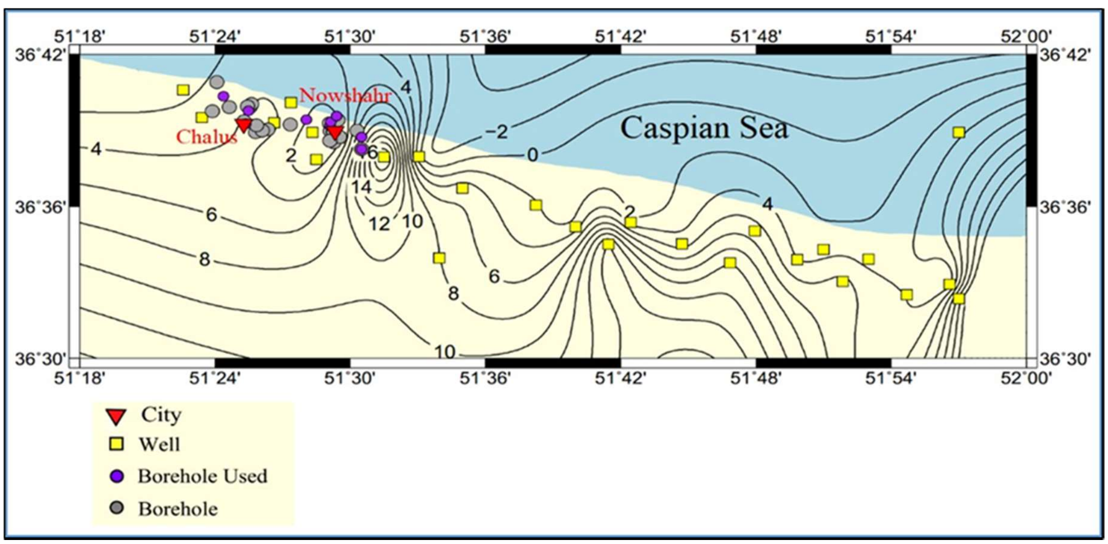


Figure 3. Map of boreholes and wells in the study area. Light purple and deep purple circles and yellow squares indicate the location of all boreholes, boreholes used in this study and wells, respectively. The black lines also indicate the water tables.

3-2 Determination of empirical correlations between Vs and N_{SPT}

Soil samples collected from different depths and boreholes dug in Chalus and Nowshahr cities were evaluated using the standard SPT penetration test (N_{SPT}) in the soil mechanics laboratory, and their geotechnical parameters such as specific gravity, density, percent moisture, modulus of elasticity and standard penetration number were obtained. It should be noted that after examining the samples, the geotechnical parameters of 16 boreholes were suitable for use in this study. Figure 4 shows an example of the geotechnical profile used in this paper to obtain the relationship between the shear wave velocity and the standard penetration number. A sample of geotechnical test is shown in Figure 4.

Exploratory Boring Log

Site: Nowshahr | Ground Eleve: 0.0

Drilling M.: Washboring | Boring No.: BH1

Total Depth: 12.0

Ground Water Eleve. 4.0 m

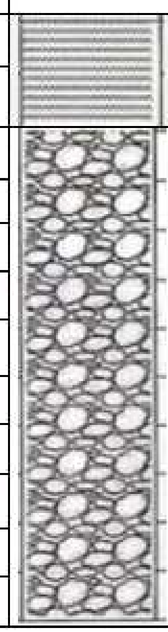
Depth (m)	Sample Depth (m)	Soil Classification	Graphic Log	Standard Penetration Test No. of Blows N	W %	Gs	γ (gr/cm³)	P_{200} (%)
1.0	1.0	ML		11	21.51	2.75	1.82	57.85
2.0	2.0	ML		19	17.86	2.69	1.94	37.83
3.0	3.0	GM		60	1.82	2.75	2.08	7.39
4.0								
5.0								
6.0	6.0	GM		67	4.77	2.73	2.15	10.05
7.0								
8.0	8.0	GM		73	4.42	2.78	2.13	10.06
9.0								
10.0	10.0	GM		73	4.16	2.68	2.13	21.10
11.0								
12.0	12.0	GM		78	5.02	2.74	2.14	9.39

Figure 4. An example of the geotechnical profile used in this study.

As said before, the determination of shear wave velocity using seismic methods is costly and experimental methods can be used to determine this parameter. In this study, the value of V_S was obtained indirectly by using the Eq. (1):

$$V_s = \sqrt{(G/\rho)} \quad (1)$$

where G and ρ are the shear modulus and density of the soil, respectively.

The shear modulus is obtained using Eq. (2):

$$V_s = \sqrt{(G/\rho)} \quad (2)$$

where E is the modulus of elasticity and ν is Poisson's ratio. The modulus of elasticity was obtained from the soil mechanics laboratory and for Poisson's ratio, the relation of Bowles (1997) was used. After calculating the shear wave velocity in each layer and obtaining $(N_1)_{60}$, which is corrected SPT blow count normalized to 60 % energy (corrected standard penetration number), the graph of changes in shear wave velocity in terms of $(N_1)_{60}$ was drawn by Excel software to obtain the relationship between V_S and $(N_1)_{60}$. Figure 5 shows the correlation between the shear wave velocity with the corresponding standard penetration number and the best fit curve for all soils of the studied range.

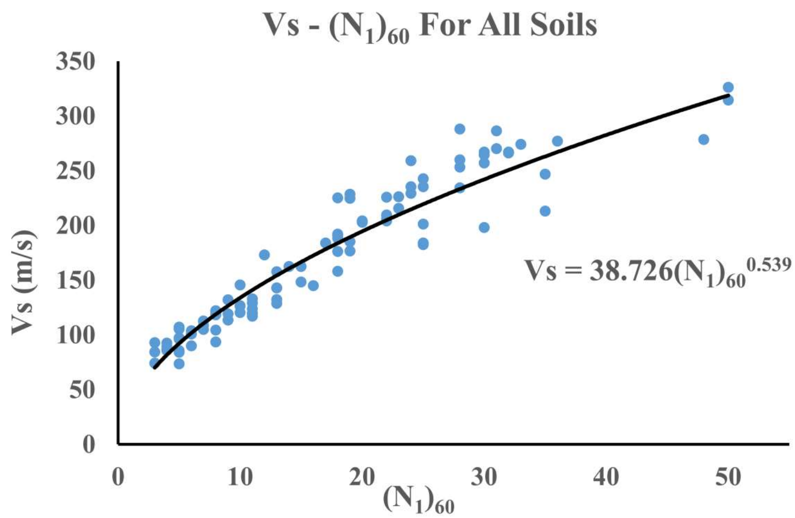


Figure 5. Correlation between Vs and $(N_1)_{60}$ for all soils.

Also, the correlation relationship between shear wave velocity and its corresponding $(N_1)_{60}$, for all soils, after regression analysis is shown in Eq. (3):

$$Vs = 38.726(N_1)_{60}^{0.539} \quad ; \quad R^2 = 0.9142 \quad (3)$$

where V_S is shear wave velocity in (m/s).

In the next step, the samples used in this study were divided into two categories: cohesive soils and non-cohesive soils. Figs. 6-a and 6-b show the correlation between V_S and $(N_1)_{60}$ for cohesive and cohesionless soils, respectively, along with the best fit curve. Eqs. (4) and (5) express the proposed correlation between shear wave velocity and its corresponding $(N_1)_{60}$, respectively, for cohesive and cohesionless soils of the studied range.

$$Vs = 31.241(N_1)_{60}^{0.626} \quad ; \quad R^2 = 0.9367 \quad (4)$$

$$Vs = 42.515(N_1)_{60}^{0.496} \quad ; \quad R^2 = 0.9283 \quad (5)$$

4 Discussion

Based on the investigations, the variables that affect the experimental relationships of the shear wave velocity of soils are: soil type, density, granularity, moisture percentage, soil depth where the soil is situated, porosity percentage, relative density, pre-consolidation percentage especially in fine-grained soils and the groundwater level. Due to the correction N for the effective overburden stress, its effect on the shear wave velocity is neglected.

The summary of the equations proposed in this study is given in Table 4. According to this table, we observed that for present data pairs, the relationship of all soils and cohesionless soils are very close because in all soils most of the data pairs are those of cohesionless soils.

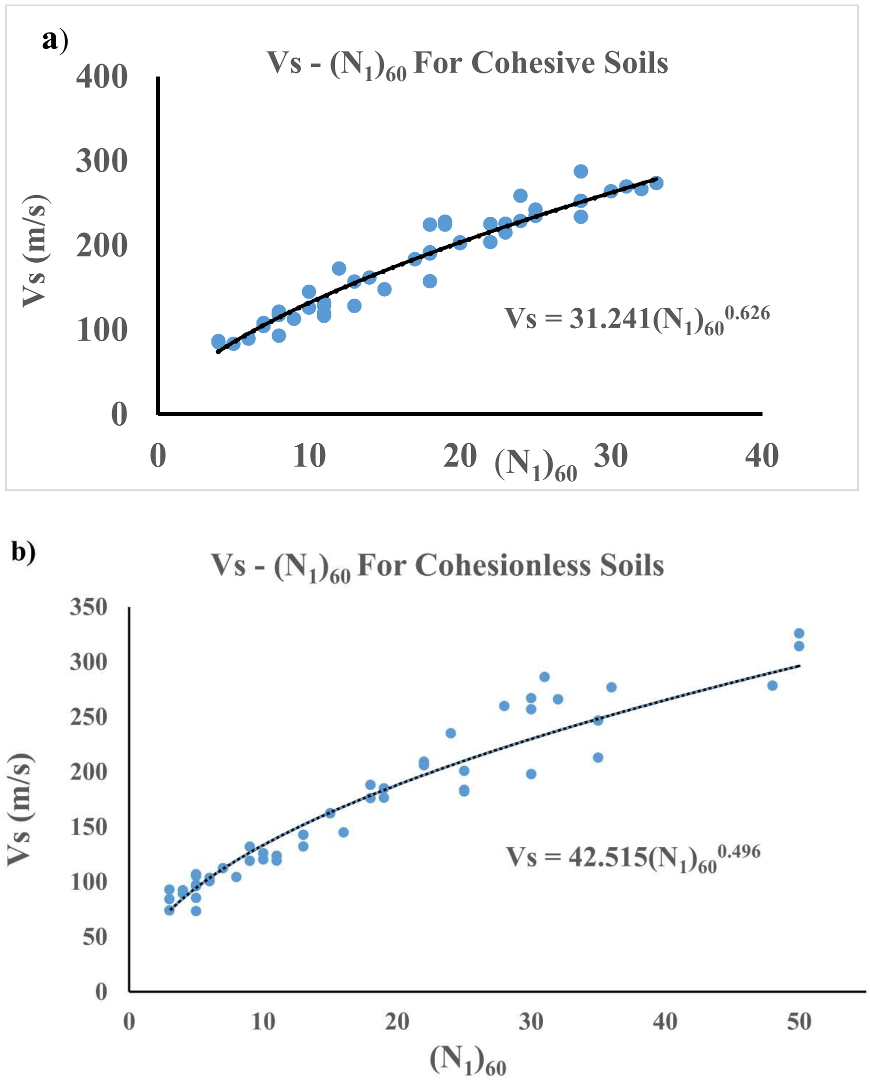


Figure 6. (a) Correlation diagram between Vs and (N1)60 for cohesive soils .(b) Correlation diagram between Vs and $(N_1)_{60}$ for cohesionless soils.

In the following, the relationships obtained for all three types of soils (all soils, cohesive and cohesionless soils) are compared with some of the previous regression equations proposed by other researchers.

Table 4. Summary of proposed relationships for all three classifications in this study.

S. no.	Type of soil	Correlation	R^2
3	All soils	$Vs = 38.726(N_1)_{60}^{0.539}$	$R^2 = 0.9142$
4	Cohesive soils	$Vs = 31.241(N_1)_{60}^{0.626}$	$R^2 = 0.9367$
5	Cohesionless soils	$Vs = 42.515(N_1)_{60}^{0.496}$	$R^2 = 0.9283$

Figure 7 shows comparisons between proposed relation (Eq. 3) and previous correlations for all soils. According to the figure, it can be seen that the curve of present study is almost in the middle of all other curves, and is in good agreement with Ohta and Goto (1978), Lee and Tsai (2008), and Tavakoli et al. (2014) in different ranges of N.

The comparison for cohesive soils given in Figure 8 reveals that the result of the this study (Eq. 4) for N< 20 is very close to that reported by Dikmen (2009) and Hasancebi and Ulusay (2007). Furthermore, at 20 <N< 35, it is approximately near to that reported by Imai (1977) and Ashikuzzaman et al. (2021) and for N > 35 it is close to that presented by Tsiambaos and Sabatakakis (2011), Ashikuzzaman et al. (2021), Lee (1990) and Kirar et al. (2016).

The comparison of the proposed relationship (Eq. 5) for cohesionless soils with previous research is shown in Figure 9. It can be observed that the result of present study is very close to that reported by Raptakis et al. (1995) and Dikmen (2009) for N < 35. Furthermore, it is approximately near to that presented by Imai (1977), Hasancebi and Ulusay (2007), Lee and Tsai (2008) and Tsiambaos and Sabatakkis (2011) for N > 35.

According to Figs. 7-9, there are differences between the existing and proposed correlations in this study. As mentioned earlier, the reason for these differences may be due to the specific geotechnical conditions of the study area, geological age, excessive consolidation or water level fluctuations as well as the accuracy of the data obtained from the experiment and shear wave velocity measurement methods which significantly affects the correlations.

4 Conclusions

The shear wave velocity (Vs) is a key parameter in ground response analysis which helps in finding amplification at a site. Moreover, Vs is the most important parameter which represents the stiffness of the soil layers. Determining shear wave velocity by seismic methods and laboratory measurements is accurate, but generally expensive. Therefore, the need to estimate shear wave velocity using other soil parameters is justified. For this purpose, the correlation obtained from the results of the standard penetration test (NSPT) with the shear wave velocity is used. In this study, an attempt has been made to develop new relationships between Vs and N for Chalus and Nowshahr region. This was carried out for three cases separately, i.e., all soils, cohesive soils and cohesionless soils. The major conclusions drawn from this study are:

1- The relationships proposed in this study (Table 4) are within the range of other existing relationships for all three categories (all soils, cohesive soils and non-cohesive soils).

2- The results obtained from this study are in good agreement with the findings of previous works.

3- Such relationships are not reported previously for this region. These relationships can be used to find shear wave velocity (Vs) as often N values are readily available.

4- Based on the analysis of the results of this study, the proposed relationships have the highest R^2 for all three types of soil compared to the correlation relationships of previous studies for similar areas such as Esfahanizadeh et al. (2015), Tavakoli et al. (2014) and Farrokhzad and Choobbasi (2016).

Also, differences between existing and proposed correlations are seen in this study. The cause of these differences may be related to the specific geotechnical conditions of the study area, geological age, excessive consolidation or fluctuations of the ground water level, which significantly affect the correlation relationships. Applying any of the existing experimental relationships is suitable for areas whose soils are the same or close to each other in terms of type, strength or density, porosity, and the ground water level.

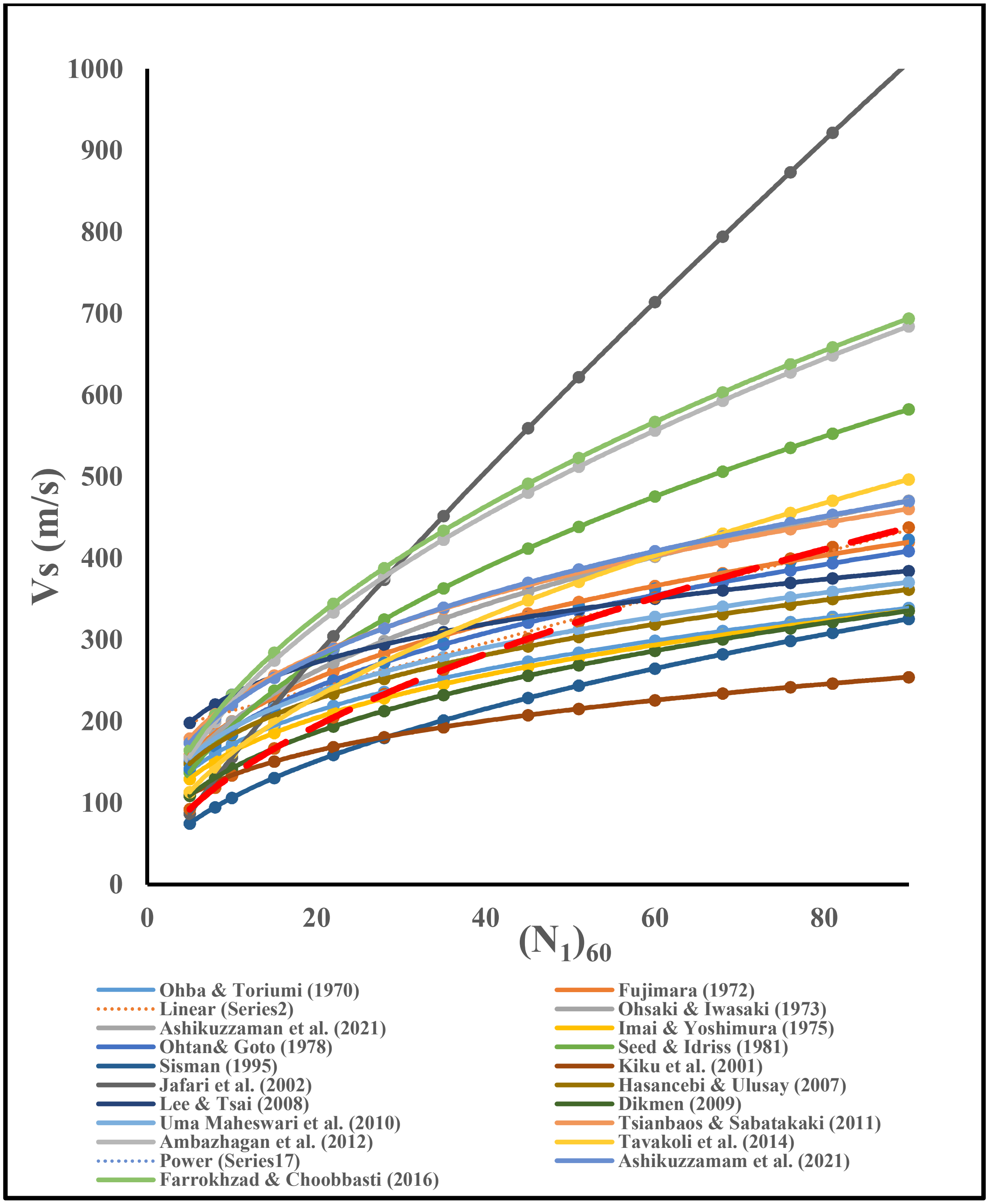


Figure 7. Comparisons between proposed correlations in present study and previous correlations for all soils.

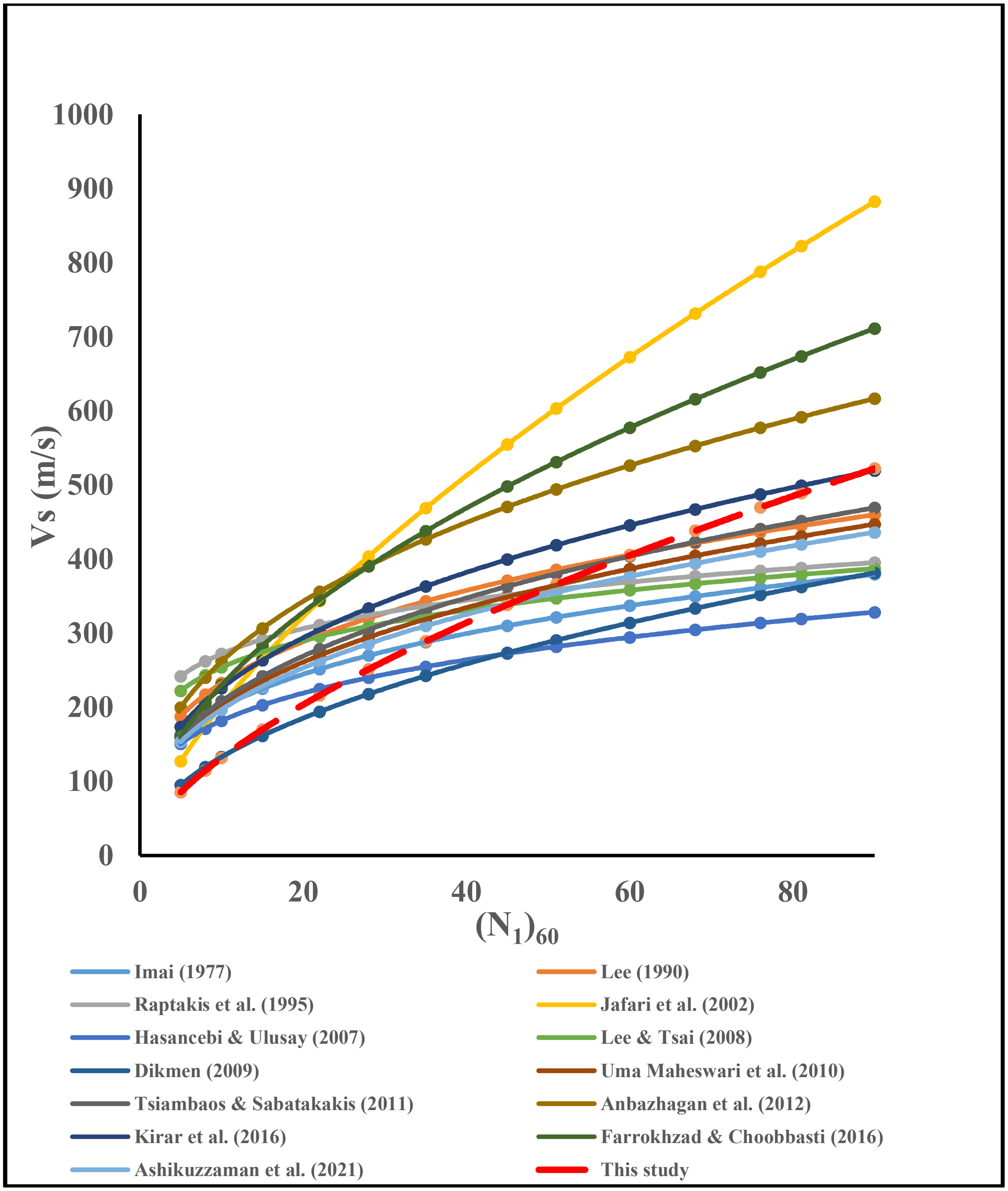


Figure 8. Comparisons between proposed correlations in present study and previous correlations for cohesive

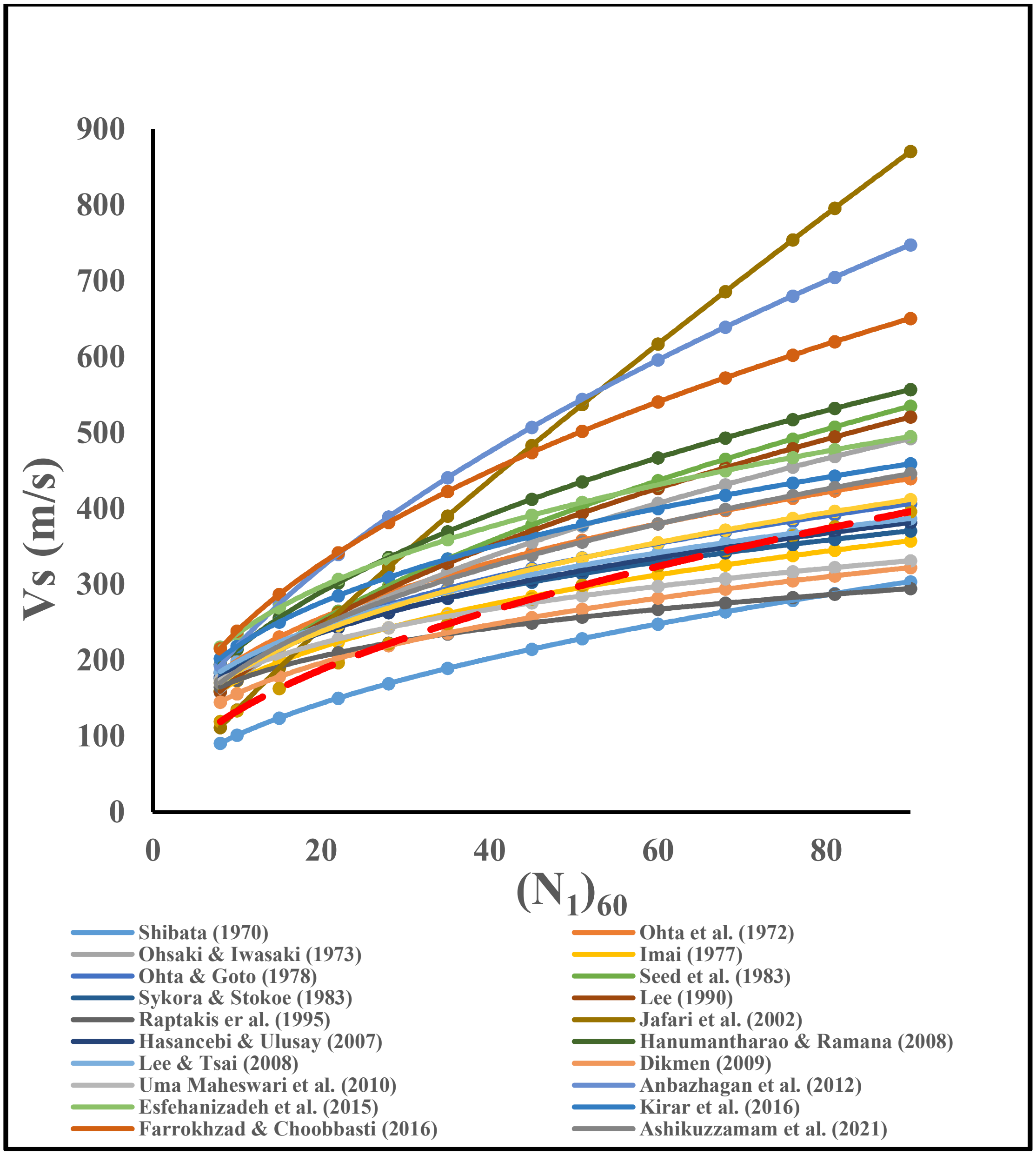


Figure 9. Comparisons between proposed correlations in present study and previous correlations for non-cohesive soils.

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