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Site Response Analysis and Empirical Correlations between N-Values and Shear Modulus for Sub-Himalayan District Hamirpur using ProShake

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Abstract

In the present work, the empirical correlations between standard penetration test (SPT) N-values versus shear modulus (Gmax), and Peak Ground Acceleration (PGA) amplifications for sub-Himalayan district-Hamirpur, Himachal Pradesh (India) consisting of highly variable soil/rock strata at different depths and across the terrain are evaluated. In the first stage, the N values obtained from SPTs are conducted in the field at 184 locations covering the studied area. The shear wave velocity for each soil profile of each borehole is calculated using the best available correlation in the literature. Further, the seismic response parameters are evaluated for these values using the ProShake software. Finally, the empirical relationships between maximum shear modulus and SPT value for different soil types are determined along with the ground motion amplifications. The amplification factor for Bhoranj sub-division varies from 1.40 to 2.60 and from 1.28 to 2.30, 1.20 to 2.10, 1.22 to 1.85, and 1.22 to 1.70 for Barsar, Nadaun, Hamirpur, and Sujanpur, respectively. The studied area consists of variable soil strata including clay, silt, sand, conglomerate, sandstone, and mixture thereof. The correlation between shear modulus and N value is coherent with already reported correlations for regular soils. The amplification factor reported for the sites plays an important role in planning infrastructure in the region. The correlations between maximum shear modulus (Gmax) and SPT value for hilly terrain comprising of highly complex geological formations such as mixed soil and fractured rocks presented in the study are not available in the research work carried out earlier.

1. Introduction

The lower Himalayan region is composed of fractured rocky strata with thin soil cover. The soil/rock strata vary significantly over short distances of every 5 to 7 km. The sub-soil profile of Himachal Pradesh has vast variations, which affects the seismic response significantly [1-3]. The state of Himachal Pradesh lies almost entirely in the Himalayan mountains with latitude 30º 22′ 40″ N to 33º 12′ 40″ N and longitude 75º 45′ 55″ to 79º 04′ 20″ E covering an area of 55,673 square kilometers. It is a mountainous state with elevation ranging from 350 m to 6000 m above the sea level, and experiences dozens of mild earthquakes every year. Major earthquakes have occurred in all parts of Himachal Pradesh in the past, and the most severe was the Kangra earthquake of 4 April 1905, with a magnitude of 7.8 (Mw).

Seismic micro-zonation studies of various other cities in India have been performed by various researchers [4-6]. The first seismic micro-zonation study was carried out in India after the Bhuj Earthquake (2001) in the Gujarat state. The Department of Science and Technology, New Delhi, first time carried out a seismic micro-zonation study in India for Jabalpur urban area (367 sq. km., zone III) in 2005. The conventional Nakamura techniques developed by Nakamura [7] were used to estimate predominant frequencies and amplifications. The authors validated the results using the Multichannel Analysis of Surface Waves (MASW) technique. Seismic hazard analysis carried out using Deterministic Seismic Hazard Analysis (DSHA) and the peak ground acceleration maps were developed based on the attenuation

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relation developed by Joyner and Boore [8]. The seismic micro-zonation map of Chennai city (426 sq. km., zone III) was prepared by Ganapathy [6] classified city into three zones, i.e. high, moderate and low; in terms of seismic hazards, which served a useful information for construction, planning of forthcoming buildings in the city, and as a base to identify the seismic risk of the city. Nath et al. [4] carried out micro-zonation studies of two Indian provinces of Sikkim Himalayas and Guwahati city to quantify the site response through horizontal-to-vertical spectral ratio method and generalized inversion approach (GINV) developed by Boatwright et al. [9]. Sikkim Himalayas region was divided into five zones according to Bureau of Indian Standards [3]; and found to be in zone V according to PGA values; and zone IV according to BIS zonation. Likewise, Guwahati city lies in zone IV, whereas as per BIS zonation it is in zone V. Barua [5] carried out seismic micro-zonation of Dehradun using MASW method and SHAKE 2000 programme for the site response studies. The data obtained from geological and geo-morphological studies was utilized for the assessment of seismic hazard, liquefaction hazard modelling, and seismic microzonation. For seismic micro-zonation studies of Kolkata city, Shiuly et al. [10] used the seismic wave propagation technique SHAKE 2000, and prepared contours of amplification at fundamental time period, average amplification and amplification at different frequency band to be used for variety of end users.

Thokchom et al. [11] suggested regression relations for the Dholera area utilizing 336 pairs of Vs–N data from MASW and PS recording at 42 and 16 locations. Fattah et al. [12] selected two locations inside the city of Al-Hilla to research the ground response study using the Proshake software, and concluded that the peak surface ground acceleration varied from 0.0523 g to 0.0639 g. The acceleration amplification factor ranges between 1.048 and 1.27. Abdullah et al. [13] evaluated the geo-technical characteristics of the locations chosen for preliminary evaluation of liquefiable zones in Kerbala city located in Baghdad, Iraq. The findings indicate that the area under investigation will be susceptible to liquefaction in the event of an earthquake with a maximum ground acceleration of 0.1 g in Kerbala city under conditions in which the soil is loose and has a relative density ranging between (25-40) %. Ghalli et al. [14] presented a framework for refining the correlation between SPT-N and geotechnical parameters in sand, and discovered that the suggested correlations might improve in estimating the angularity of particles and the coefficient of uniformity. Ataee et al. [15] estimated shear wave velocity of soil in Mashhad city using standard penetration test (SPT) blow counts. The results showed that the N-value was the most important factor in estimating Vs, while the type of soil was less important. Using computational approaches such as ANN and NLR, [17] calculated the empirical correlations between shear wave velocity and SPT-N value for Indore city. These approaches helped to establish a correlation with least error R^2, and the highest R^2 values (nearly 1) achieved using ANN methods. Rao and Choudhury [18] evaluated geo-technical data from 142 boreholes placed across the newly planned nuclear power plant (NPP) state in the north-west of India. Duan et al. [19] suggested a group method of data handling (GMDH)-optimized neural network to estimate the state parameter using CPT data compiled from the historical liquefaction database. It was revealed that the use of the GMDH model for assessing the in situ condition of sand, and subsequent evaluation of its liquefaction potential showed positive outcomes. An empirical relationship between Vs and SPT-N was developed by using geotechnical investigation reports data of twenty sites in Metro Manila [20]. The newly obtained empirical correlations for the three types of soil found to be consistent with previous studies on this subject by researchers across the world. Kumar et al. [21] proposed a set of correlations between standard penetration number (SPT-N) and shear wave velocity (VS) using non-linear regression analysis for various classifications of soil in the city of Amaravati. In the absence of direct measurements of Vs in the field, the generated correlations may be utilized to obtain VS profiles of the research area. Duan [22] investigated the uncertainty in a state parameter-based model of liquefaction resistance and potential evaluation for the simplified procedure of [23]. The findings show that a mean of 1.03 and a coefficient of variation of 0.12 may be used to characterize uncertainty in the state parameter-based model. Zhao et al. [24] established a fully probabilistic framework for liquefaction potential assessment in an effort to eliminate model and parameter uncertainties that might result in an inappropriate geo-technical design, and found that the proposed framework provides accurate predictions of liquefaction and may be used as an alternative technique to deterministic evaluations.

Depending on the site soil strata, the seismic wave energy gets amplifed or de-amplified when it travels through multiple soil layers resulting in dynamic loads. Dynamic loads may weaken the structures and reduce their reliability level [25-28]. From the previous earthquake histories, if the site amplifcation is not reviewed while designing a structure, it might be causing large deformations and collapse of the structure [29, 30].

In all the seismic micro-zonation studies carried out by various researchers and in view of literature review concluded that most of the studies have been conducted in areas consisting of soil strata of single type of soil and research areas lie in lower seismic zones (II and III). The lower Himalayan region is comprised of fragmented rocky layers that covered in a thin layer of soil. The soil and rock layers undergo significant changes over relatively short distances. Himachal Pradesh's subsoil profile varies greatly, which has a major impact on the region's seismic response. Therefore, a study needs to be undertaken to investigate the seismic response of Himachal Pradesh at micro-level consisting of different layers. For the current study Hamirpur district located in lower Himalayan region of Himachal Pradesh considered to analyze the seismic response. Hamirpur is the most densely populated district, and is also having highest road density (171.83 per 100 square kilometer of the area) all over India. It lies in zone V (90.9% area), and is liable to severest earthquake intensity IX or more [31]. The objective of the present study is to develop empirical correlations between standard penetration test (SPT) N-values versus shear modulus (Gmax) and Peak Ground Acceleration (PGA) amplifications in terms of amplification factor for the sub-Himalayan district- Hamirpur, Himachal Pradesh (India) having highly variable soil/rock strata at different depths and across the terrain. The proposed correlations between N-values versus shear modulus and amplification factors will serve as a guide for researchers, designers and policy makers at micro level.

The terrain of Himachal Pradesh is hilly ranging from Shiwaliks in the south to tall snow clad Pirpanjals in the north. The state was shaken by earthquakes occurring in its territory but also in the neighboring areas of Jammu and Kashmir in the north, Tibet in the east, and UP hills in the southeast. The earthquake activity in HP is attributable to the Himalayan orogeny with seven earthquake of magnitude varying from 4.5 to 7.9 in the past. Thus the earthquake hazard poses biggest threat to the state. Seismic micro-zonation studies of various Indian cities viz. Delhi (1483 Sq. km., Zone IV), Jabalpur (367 Sq. km., Zone III), Guwahati (216 Sq km, Zone V), Kutch (170 Sq. km., Zone V), Chennai (426 Sq. km., Zone III), Kochi (630 Sq. km., Zone III), Bangalore (220 sq. km., Zone III) and Vishakhapatanam (544 Sq. km., Zone II) were performed by different researchers [6, 10, 18, 32]. Only a limited study is available in the literature for similar strata. Hamirpur district is one of the 12 districts of Himachal Pradesh, which lies in the sub-Himalayan zone with non-linear soil strata having variable density with depth covering an area of 1118 square km and lies in seismic zone V. The population density of the district is 407 per square km. The present study has its wide applicability for similar strata covering the entire sub-Himalayan zone.

The present study provides an insight into correlations between SPT and shear modulus covering highly variable soil/rock strata in seismic zone V in the west Himalayan area. It includes developing empirical correlations between SPT and shear wave velocity of sub-Himalayan area wherein mixed type of soil and rock strata exists at various depths and laterally spread across the terrain. The earlier studies have been limited to soil strata predominantly of one type, and no study was conducted in the sub-Himalayan zone specifically western Himalayan zone covered under seismic zone-V. The peak ground acceleration values evaluated in the present study shall be of immense applicability for assessing the damage to the existing structures as well as future planning and designing of structures in the study area.

2. Methodology

The present work includes the estimation of peak ground accelerations, amplification factor, and empirical correlations between shear modulus and SPT-N values. In the first stage, standard penetration tests are conducted in the field at 184 borehole locations up to 30 m depth spread over the entire Hamirpur district covering five administrative sub-divisions. When the borehole is drilled to the desired depth, the drilling tools were removed, and standard split-spoon sampler was lowered to the bottom of the borehole. Then the sampler was driven into the soil by a drop hammer of 63.5 kg mass falling through a height of 750 mm at the rate of 30 blows per minute [33]. The number of blows required to drive the first 150 mm penetration of the sampler was recorded. The sampler was further driven by 300 mm, and the number of blows was recorded at an interval of 150 mm penetration. The number of blows recorded for the first 150 mm penetration was disregarded, and the number of blows recorded for the last two 150 mm intervals was added to give the SPT-N value of the particular soil profile in the concerned borehole. The observed SPT-N values were then corrected for energy, overburden, and dilatancy corrections. The in-situ density of each sub-soil layer wass determined in the laboratory. The shear wave velocity (Vs) for each soil profile of each borehole was calculated using the correlation developed by Tamura and Yamazaki [34] for all types of soils. A similar type of soil layers was encountered in one particular borehole grouped under one soil column. The corresponding SPT-N (corrected), in-situ density, and shear wave velocity values were averaged out and assigned to that particular soil column. Typical borehole log data was observed from standard penetration test for the borehole log numbers 67, 64, 51, 93, and 3 lying in Barsar, Hamirpur, Nadaun, Bhoranj, and Sujanpur sub-divisions, respectively, of Hamirpur district are shown in Table 1. In the second stage, the seismic response parameters were evaluated for individual soil columns using the ProShake software under three different earthquake motions of varying magnitudes from 6.9-7.2. The average values of SPT-N (corrected), density, shear wave velocity, and earthquake motion were used as the input parameters to calculate the seismic response parameters for each soil column. From the in-built soil models and input earthquake motions in the ProShake software, particular soil model and input motions were assigned to each type of soil column. Using the output manager option in the software seismic response parameters were evaluated for each type of soil column under different earthquake motions assigned during analysis. Finally, empirical relationships between maximum shear modulus (G_{max}) and standard penetration test (SPT) value for different soil types were determined along with the ground motion amplifications.

2.1. ProShake software

ProShake is a one dimensional, equivalent linear ground response analysis computer programme. It is an effective and simple software program. It includes many features that make data entry, analysis, viewing, and documenting results more efficient and effective such as built-in modulus reduction and damping models, graphical displays of soil profile, and input motion parameters, graphical displays of a wide range of output parameters, and animation of ground response. The input manager arranges the input data into projects, which include numerous soil profiles and each project contains soil profile data and ground motion data. Site response analyses are run in the solution manager, while the output manager present data in a variety of helpful charts and export it to a variety of spreadsheet formats for use in other graphical programs or long-term storage. The soil behavior is non-linear but this non-linear hysteretic stress-strain behavior has been approximated by equivalent linear soil properties in the ProShake software [35]. It assumes the vertical propagation of shear waves from a uniform half space through horizontal layers of a soil profile modelled as visco-elastic material having constant damping ratios across all frequencies. This equivalent linear approach has been coded into the ProShake software. The past studies performed using the ProShake software to obtain seismic response analysis show that the results are in a good agreement when compared with other software programs such as SHAKE91, SHAKEVT, Strata, and DEEPSOIL [36, 37].

2.1. Shear wave velocity (Vs)

In micro-zonation studies as well as in design codes worldwide, site effects are taken into account for seismic micro-zonation of different sites. Shear modulus is a key parameter for determining the dynamic soil properties, which are used for characterization of seismic sites. There are various methods such as borehole methods (cross-hole, up hole, down hole, and suspension logging) and surface wave methods (spectral analysis of surface waves, multi-channel analysis of surface waves, and refraction micrometer) for measuring the surface wave velocity [38]. The most popular methods that have been recommended in design codes for seismic site classifications are those that consider bore logs with standard penetration test N-values (SPT-N) and shear wave velocities (Vs) from spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves [39]. The National Earthquake Hazards Reduction Program (NEHRP), Building Seismic Safety Council [40], and the International Building Code [41] have also recommended the use of average values of Vs or SPT-N of top 30-m soil layers in seismic site classification methods.

MASW is increasingly applied in earthquake geo-technical engineering for seismic microzonation and site response studies. The sub-soil profile of Hamirpur is having vast variations ranging from soft soil to hard soil/rock having very soft intermediate layered strata. The MASW method being an indirect method is not reliable because it will not give information about the soft soil layer, if any, encountered in between the hard layers, thus not representing the true profile. It is preferable to determine Vs directly from field tests but it is often not economically feasible to make Vs measurements at all locations. Various researchers have proposed correlations between Vs and penetration resistance (SPT-N) for different type of soils such as sand, silt, and clays. However, the correlation proposed by Tamura and Yamazaki [34] are for all types of soils and this considers the effect of both N and depth (D) of soil strata, hence has been used in the present work for computation of shear wave velocity.

Table 1. Typical bore log data profile used for analysis.

Borehole No. and location	**Depth (m)**	**Soil type from bore hole data**	**Corrected SPT-N value**	**Water table depth (m)**	**Density (kN/m^3)**	**Shear wave velocity (m/s) $Vs = 105.8 N^{0.187} D^{0.179}$** (Tamura and Yamazaki; 2002)
Barsar sub-division (76° 37' 23", 31° 41' 18")						
67		**Soft clay mixed with pebbles, gravels, and boulders**		33.00		
	1.50	Soft	8		18.4	167.84
	3.00	Soft	10		18.4	198.10
	4.50	Soft to medium	13		18.5	223.73
	6.00	Medium	17		18.6	247.67
	7.50	Medium	21		18.6	268.15
	9.00	Medium	23		18.6	281.80
	10.50	Medium	26		18.6	296.40
	12.00	Medium	28		18.6	307.81
	13.50	Medium to stiff	31		18.7	320.41
	15.00	Medium to stiff	33		18.7	330.35
	16.50	Medium to stiff	36		18.7	341.54
	18.00	Medium to stiff	39		18.7	352.13
	19.50	Medium to stiff	43		18.7	363.80
	21.00	Medium to stiff	48		18.7	376.32
	22.50	Medium to stiff	54		18.7	389.48
	24.00	Medium to stiff	60		18.7	401.84
	25.50	Stiff	64		18.8	411.16
	27.00	Stiff	67		18.8	418.96
	28.50	Stiff	70		18.8	426.52
	30.00	Stiff	72		18.8	432.72
Hamirpur subdivision (76° 31' 55", 31° 41' 24")						
64		**Medium grained brownish saturated silt**		90.00		
	1.50	Loose	10		1.8	174.99
	3.00	Loose to medium	13		1.82	208.06
	4.50	Medium	16		1.83	232.58
	6.00	Medium	20		1.83	255.31
	7.50	Medium	23		1.83	272.75
	9.00	Medium	27		1.83	290.38
	10.50	Medium	29		1.83	302.52
	12.00	Medium to hard	32		1.84	315.59
	13.50	Medium to hard	35		1.84	327.76
	15.00	Medium to hard	37		1.84	337.49
	16.50	Medium to hard	39		1.84	346.69
	18.00	Medium to hard	41		1.84	355.44
	19.50	Medium to hard	44		1.84	365.37
	21.00	Medium to hard	47		1.84	374.84
	22.50	Medium to hard	50		1.84	383.91
		Brownish dry clay				
	24.00	Medium to hard	52		1.82	391.23
	25.50	Medium to hard	53		1.82	396.91
	27.00	Medium to hard	55		1.82	403.78
	28.50	Medium to hard	56		1.82	409.09
	30.00	Medium to hard	56		1.82	412.86

Continuous of Table 1. Typical bore log data profile used for analysis.

		Nadaun sub-division (76° 27' 07", 31° 42' 47")			
51		**Greyish medium grained sand stone**	48.00		
	1.50	Loose	10	1.89	174.99
	3.00	loose to medium	14	1.90	210.97
	4.50	Medium	19	1.92	240.18
	6.00	Medium	26	1.92	268.15
	7.50	Medium to hard	34	1.93	293.43
	9.00	Medium to hard	40	1.93	312.52
	10.50	Medium to hard	47	1.93	331.10
	12.00	Medium to hard	54	1.93	348.03
	13.50	Medium to hard	59	1.93	361.38
	15.00	Hard	66	1.94	376.06
	16.50	Hard	69	1.94	385.73
	18.00	Hard	75	1.94	397.94
	19.50	Hard	76	1.94	404.68
	21.00	Hard	77	1.94	411.09
	24.00	Hard	78	1.94	422.05
		Brownish dry clay:			
	27.00	Hard	79	1.83	432.07
	30.00	Hard	80	1.83	441.33
		Bhoranj subdivision (76° 42' 04", 31° 39' 50")			
93		**Boulders conglomerate**	33.00		
	1.50	Loose to medium	15	1.98	188.77
	3.00	Medium	19	2.00	223.37
	4.50	Medium	26	2.00	254.69
	6.00	Medium to hard	32	2.01	278.76
	7.50	Medium to hard	39	2.01	301.06
	9.00	Medium to hard	45	2.01	319.48
	10.50	Medium to hard	50	2.01	334.95
	12.00	Medium to hard	60	2.01	354.96
	13.50	Hard	64	2.03	366.92
	15.00	Hard	68	2.03	378.17
	16.50	Hard	70	2.03	386.77
	18.00	Hard	70	2.03	392.84
		Clay stone			
	19.50	Hard	72	1.91	400.61
	21.00	Hard	74	1.91	408.05
	22.50	Hard	76	1.91	415.18
	24.00	Hard	78	1.91	422.05
		Boulders conglomerate			
	27.00	Hard	80	2.03	433.09
	30.00	Very hard	100	2.05	460.14
		Sujanpur subdivision (76° 32' 20", 31° 51' 47")			
3		**Boulders with sand**	27.00		
	1.00	loose to medium	16	2.00	177.69
	3.00	Medium	22	2.01	229.57
	4.50	medium to hard	45	2.02	282.20
	6.00	medium to hard	57	2.02	310.54
		Boulder conglomerate with sandy matrix			
	7.50	Hard	68	2.03	334.04
	9.00	Hard	74	2.03	350.62
	12.00	Very hard	86	2.04	379.67
	15.00	Very hard	100	2.04	406.45
	18.00	Very hard	100	2.04	419.93
	21.00	Very hard	100	2.04	431.68
	24.00	Very hard	100	2.04	442.12
	27.00	Very hard	100	2.04	451.54
	30.00	Very hard	100	2.04	460.14

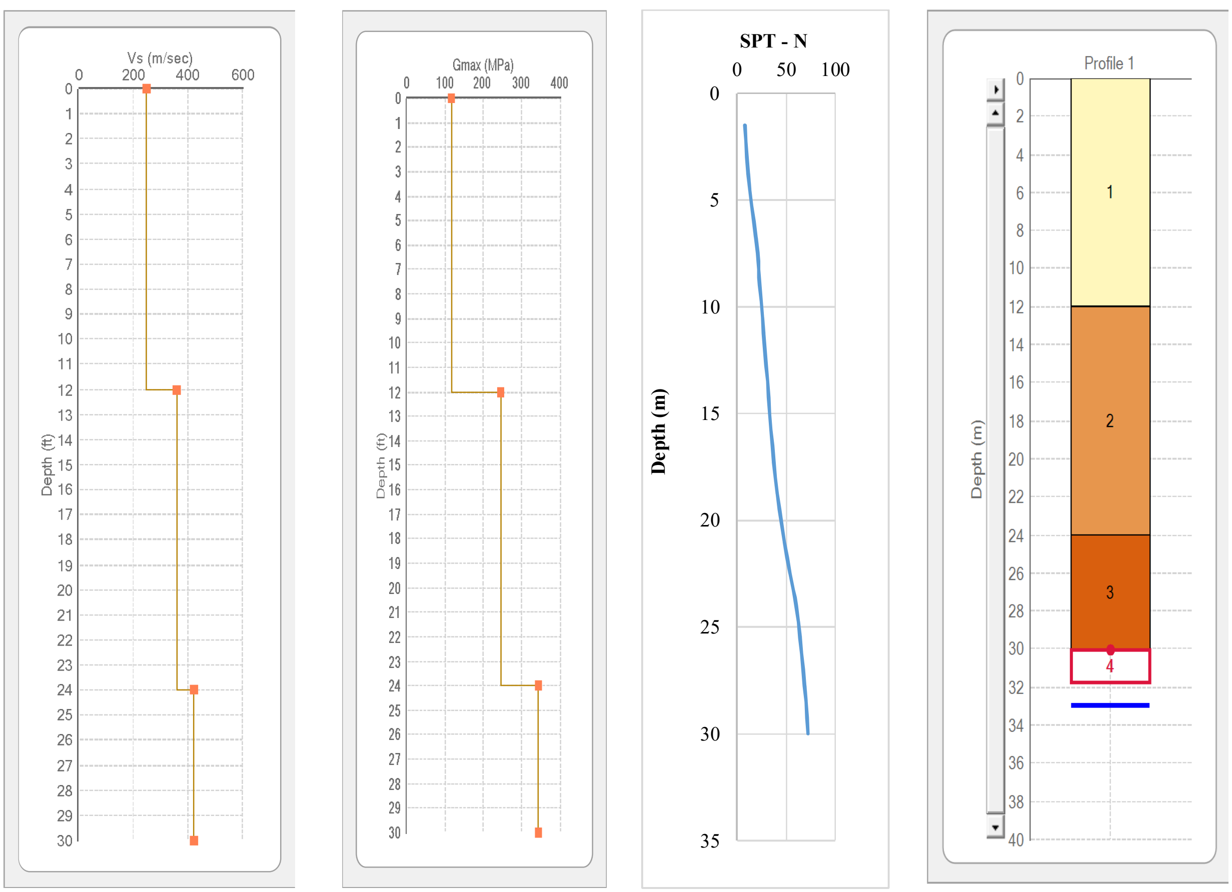
2.2. Soil profile data

Soil profile data have been collected by conducting Standard penetration tests at various locations in the Hamirpur district. The soil profile data was observed for 23 locations for Hamirpur Sub-division and for 34, 29, 42, and 53 locations of Nadaun, Sujanpur, Bhoranj, and Barsar sub-divisions, respectively, and the collected data has been used in the present work for evaluating the seismic response and developing correlations.

Figures 1(a), (b), and (c) show the variation of shear wave velocity, shear modulus, and SPT-N values with depth for one typical bore log profile (clay mixed with pebbles, gravels and boulders) of Barsar subdivision. Figure 1(d) shows the water table level in a typical bore hole. Shear wave velocity, shear modulus, and SPT-N values are the input parameters in the software for evaluation of seismic response design parameters. Figure 2 shows the location of various boreholes (184 Nos.) in the Hamirpur district that have been used for the evaluation of soil response parameters in seismic microzonation studies. The dots indicated on the map show the geographical locations of various boreholes.

2.3. Ground motion input data

The biggest ever earthquake that Himachal has experienced was the Kangra earthquake of 4th April, 1905 with magnitude of 7.8 (M_w). In this work, the ProShake software [42], which is a one-dimensional equivalent linear ground response analysis software, was used for site response studies. Three input ground motions of El Centro earthquake (M_w 6.9), Santa Cruz Loma Prieta earthquake (Mw 7.0), and Petrolia earthquake (M_w 7.2) were used for evaluation of site response parameters, which are influenced by local site conditions. These three earthquakes of magnitudes ranging from 6.9 to 7.2 were considered for the site response studies as the studied area experiencing average earthquake motion of magnitude 7.0 in the past. Table 2 shows the input motion parameters of three different earthquakes, which were used in the present work.



(a) (b) (c) (d)

Figure 1(a) Typical variation of shear wave velocity (b) Typical variation of shear modulus (c) Typical variation of SPT-N values (d) Typical borehole water table level.

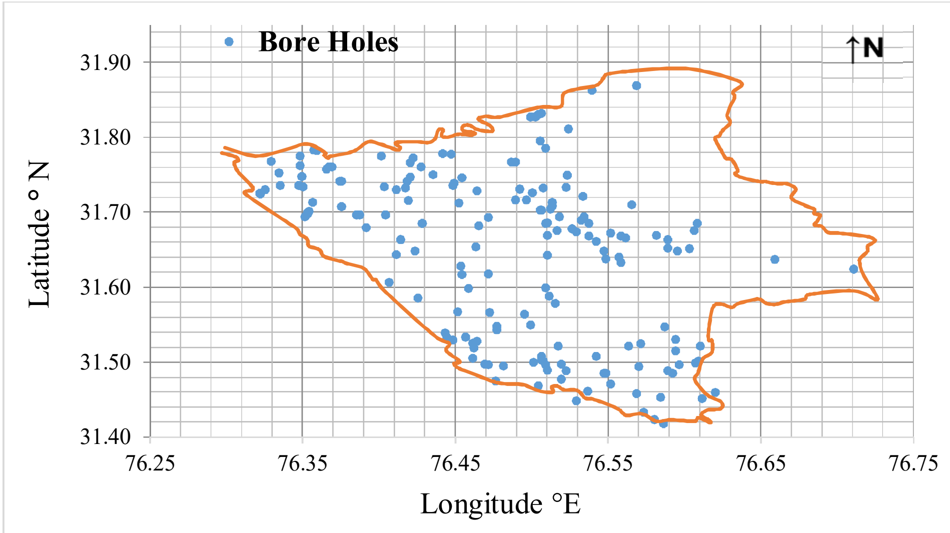


Figure 2. Location of boreholes used for analysis.

Table 2. Input motion parameter of the considered earthquakes [42].

Earthquake motion	Peak velocity (m/s)	Peak acceleration (g)	Peak Displacement (m)	Response Spectrum Intensity (g^2)	Predominant period (sec)	Spectral acceleration @1.0 sec	RMS acceleration (g)
El Centro (1940/05/18) Station = El Centro - Imp Vall Irr Dist. Component = 180 (Magnitude M_w = 6.9)	0.350	0.344	0.111	3.381	0.683	0.508	0.068
Treasure Island - Santa Cruz MTNS (Loma Prieta) earthquake (Magnitude M_w = 7.0)	0.332	0.159	0.128	3.189	0.640	0.240	0.068
Petrolia/ Cape Mendocino earthquake (1992/04/25) Station = 1023 Component = 270 (Magnitude M_w = 7.2)	0.834	0.422	0.220	6.162	1.412	0.699	0.094

Figures 3 to 5 show the comparison of output response spectra of different typical soil types under three different earthquakes with their recorded outputs. The ground motion amplification is more in soft regular soils such as clay because of damping effect, whereas in combined soils such as clay mixed with pebbles-gravels-boulders, and boulders conglomerate, the amplification is less and its degree of amplification depends upon quantum of the constituents and their spatial distribution. Also in a regular hard soil such as in sandstone, amplification is less. Seismic waves move faster in hard rock than soft soil. When they move from hard to soft, their amplitude (or size) increases and larger waves cause strong amplifications.

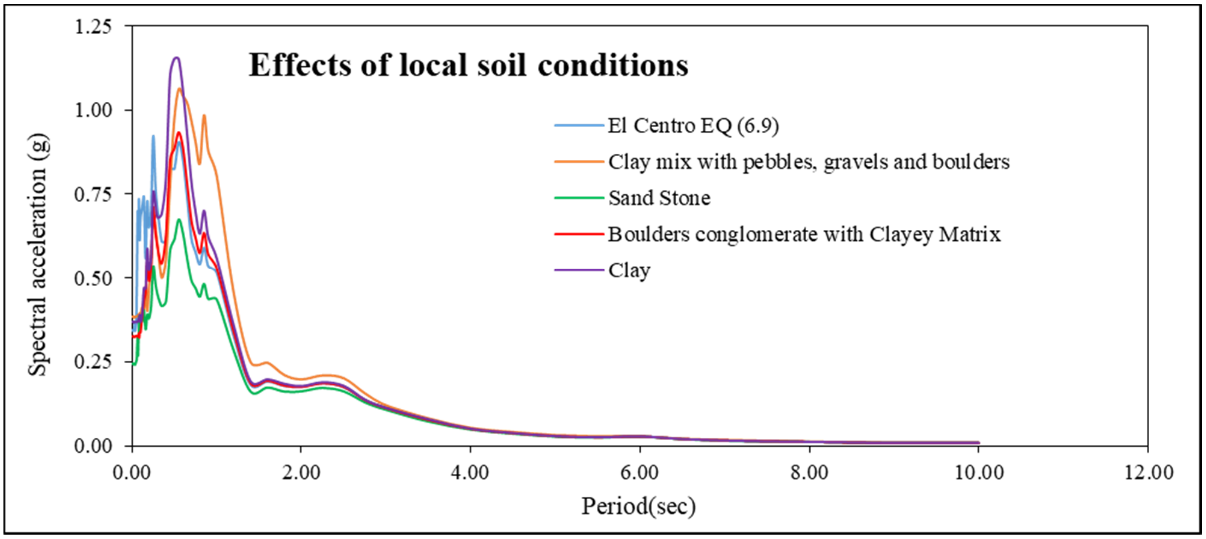


Figure 3. Comparison of response spectra for El Centro earthquake input motion and output for different typical soil classifications of Barsar sub-division.

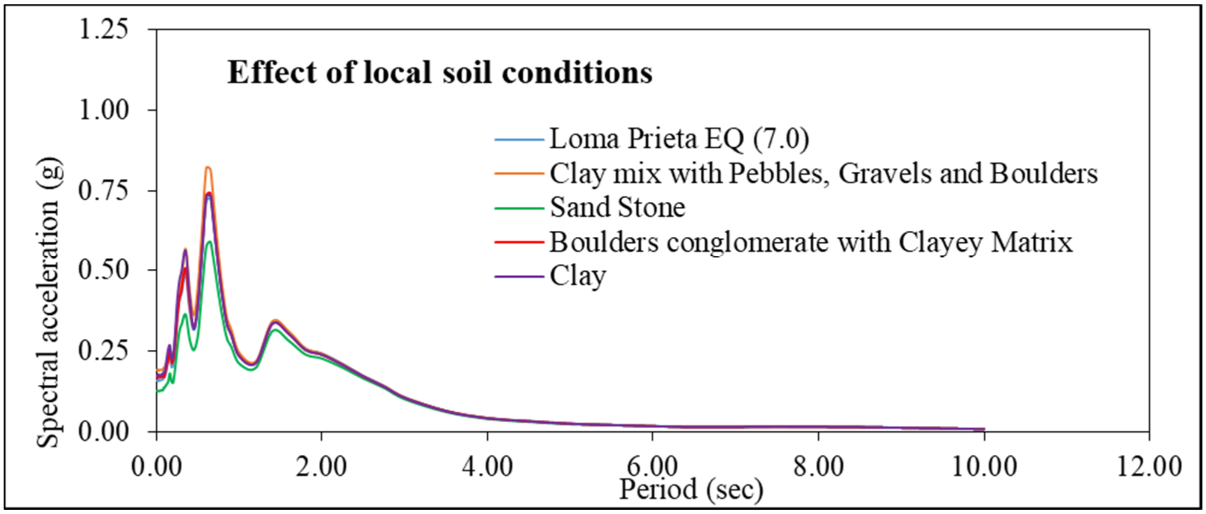


Figure 4. Comparison of response spectra for Loma Prieta earthquake input motion and output for different typical soil classifications of Barsar sub-division.

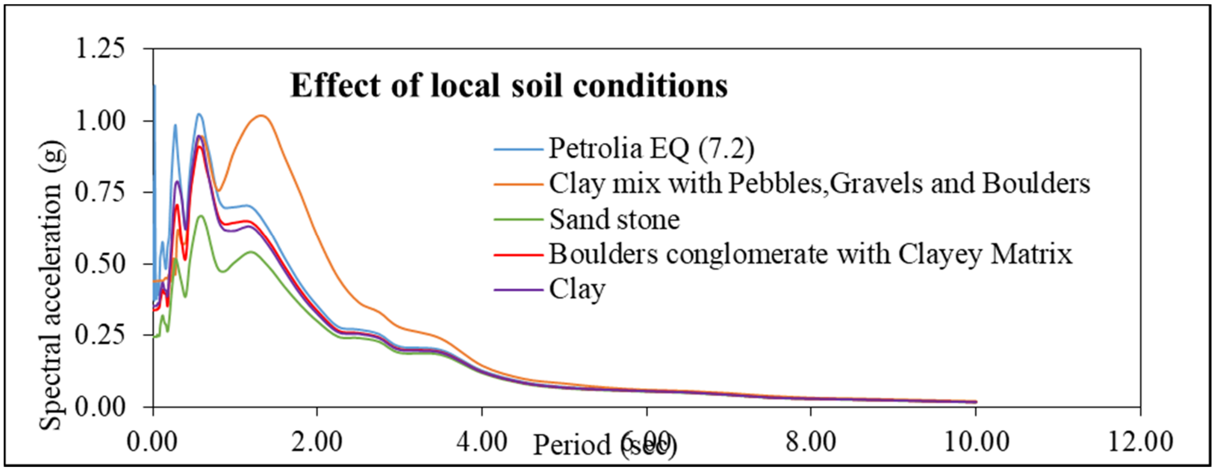


Figure 5. Comparison of response spectra for Petrolia earthquake input motion and output for different typical soil classifications of Barsar sub-division.

Site geological conditions have a considerable effect on seismic motions when they propagate through the soil medium. The amplification factor for Bhoranj sub-division varies from 1.35-2.64 under the El Centro earthquake, 1.18-1.87 under the Loma Prieta earthquake, and 1.18-2.60 under the Petrolia earthquake. At different depths varying up to 30 m in Bhoranj sub-division, the soil profiles in different boreholes are clay with unconsolidated boulders, clay with pebbles, clay, boulder conglomerate, clay with sandy matrix, medium-grained saturated silt, dry clay, boulders with clay-sand, and boulders with petronix nature. The amplification factor for Barsar sub-division varies from 1.07-2.57 under the El Centro earthquake, 1.08-1.67 under the Loma Prieta earthquake, and 1.10-2.45 under the Petrolia earthquake. At different depths varying from top 20-30 m in Barsar sub-division, the soil profiles in different boreholes are clay mixed with pebbles + gravels + boulders, sand stone, clay with boulders, clay mixed with pebbles + gravels + boulders, sand stone, boulder conglomerate with clayey matrix, clay stone with boulders, loose clay with unconsolidated boulders, and boulders mixed with clay. The amplification factor for Nadaun sub-division varies from 1.29-2.34 under the El Centro earthquake, 1.11-1.59 under the Loma Prieta earthquake, and 1.14-2.22 under the Petrolia earthquake. At different depths varying from top 21-30 m in Nadaun sub-division, the soil profiles in different boreholes are boulders with sand, boulders, clay + sand + pebbles, saturated silt, sand stone and clay mixed with boulders. The amplification factor for Hamirpur sub-division varies from 1.37-2.07 under the El Centro earthquake, 1.13-1.47 under the Loma Prieta earthquake, and 1.13-1.86 under the Petrolia earthquake. At different depths varying up to 30 m in Hamirpur sub-division, the soil profiles in different boreholes are medium-grained saturated sandy silt, medium-grained saturated sandy silt, conglomerate with sandy matrix, sand stone, dry clay, conglomerate unconsolidated, boulders with sand and clay. The predominance of soft soils results in more amplification of input motions. The amplification factor for Sujanpur sub-division varies from 1.29-2.13 under the El Centro earthquake, 1.13-1.52 under the Loma Prieta earthquake, and 1.14-2.04 under the Petrolia earthquake. At different depths varying up to 30 m in Sujanpur sub-division, the soil profiles in different boreholes are boulders, conglomerates with sandy matrix, boulders mixed with clay, loose boulders with sand, clay mixed with pebbles + boulders, and medium grained saturated silt. The variation in the amplification factor in each sub-division under three different earthquake motions is due to different input acceleration time history and soil profiles at the site. Figure 6 shows the combined variations of amplification of peak ground acceleration under different earthquake motions for all sub-divisions.

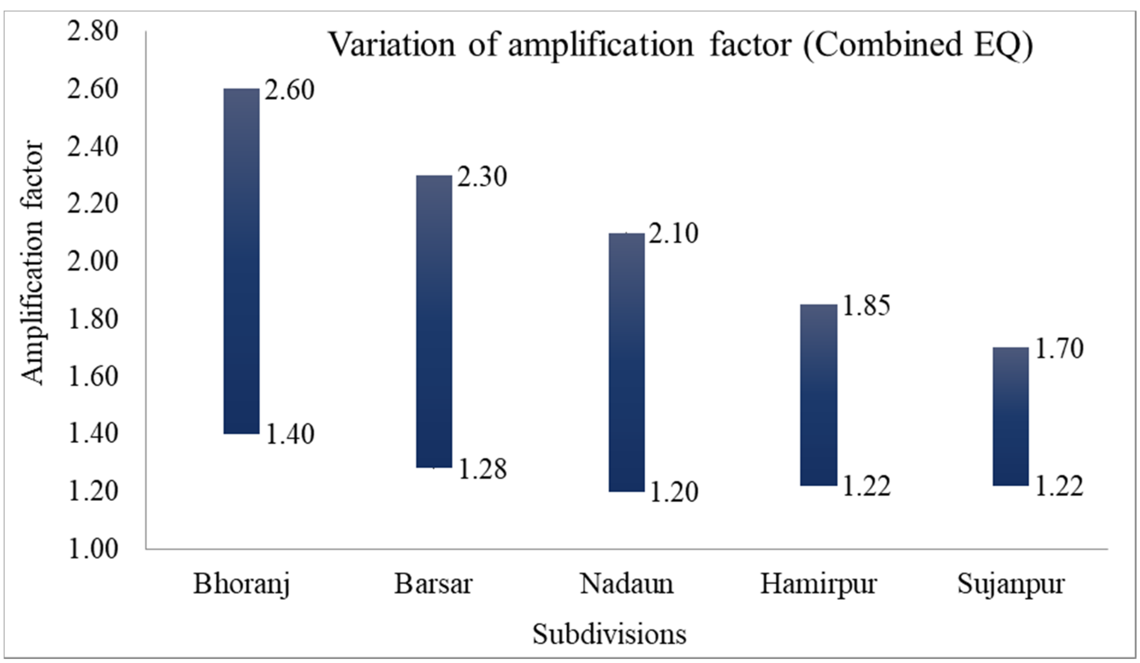


Figure 6. Variation of PGA amplification factor for all earthquakes.

Table 3. Some existing correlations between Vs and SPT-N.

Author(s)	V_s (m/s)			
	All soils	**Sands**	**Silt**	**Clays**
Ohba and Toriuma [43]	$84 N^{0.31}$	-	-	-
Imai and Yoshimura [44]	$76 N^{0.33}$	-	-	-
Fujiwara [45]	$92.1 N^{0.337}$	-	-	-
Ohsaki and Iwasaki [46]	$82 N^{0.39}$	-	-	-
Imai [47]	$91 N^{0.337}$	$80.6 N^{0.331}$	-	80.2
Ohta and Goto [48]	$85.35 N^{0.348}$	-	-	-
Seed and Idriss [49]	$61 N^{0.5}$	-	-	-
Imai and Tonouchi [50]	$97 N^{0.314}$	-	-	-
Sykora and Stokoe [51]	-	$100.5 N^{0.29}$	-	-
Jinan [52]	$116.1 (N+0.3185)^{0.202}$	-	-	-
Lee [53]	-	$57.4 N^{0.49}$	$105.64 N^{0.32}$	$114.43 N^{0.31}$
Sisman [54]	$32.8 N^{0.51}$	-	-	-
Iyisan [55]	$51.5 N^{0.516}$	-	-	-
Jafari et al. [56]	$22 N^{0.85}$	-	-	-
Pitilakis et al. [57]	-	$145(N60)^{0.178}$	-	$132 N60)^{0.27}$
Kiku et al. [58]	$68.3 N^{0.292}$	-	-	-
Jafari et al. [59]	-	-	$22 N^{0.77}$	$27 N^{0.73}$
Tamura and Yamazaki [34]	$105.8 N^{0.187} D^{0.179}$	-	-	-
Dikmen [60]	$58 N^{0.39}$	$73 N^{0.33}$	$60 N^{0.36}$	$44 N^{0.48}$
Uma Maheshwari et al. [61]	$95.64 N^{0.301}$	$00.53 N^{0.265}$	-	$89.3 N^{0.358}$
Fauzi et al. [62]	$105.03 N^{0.286}$		-	
Daag A.S. et al. [20]	$56.82 N^{0.4861}$	$45.07 N^{0.5534}$		$70.26 N^{0.4220}$
Kirar et al. [63]	$99.5 N^{0.345}$	$100.3 N^{0.338}$		$94.4 N^{0.379}$
Shiuly and Roy [64]	$76.969 N^{0.3770}$	$83.608 N^{0.3517}$	$81.15 N^{0.3856}$	$93.422 N^{0.33527}$

3. Results and discussion

3.1. Correlation between SPT N and shear modulus (G_{max})

The site response parameters of Hamirpur district were determined in the present work by performing equivalent linear analysis using the ProShake software (site response programme) for three earthquakes of magnitude 6.8, 7.0, and 7.2. Earthquakes of magnitudes below 6.5 are not in general severely damaging, and the most devastating earthquake experienced in Himachal Pradesh is Kangra earthquake having magnitude 7.8, so earthquakes of magnitude ranging from 6.8 to 7.2 were considered for site response study of the Hamirpur district. Different soil columns behave differently for different earthquakes so the soil strata up to 30 m depth were grouped into six soil categories for site response studies, and accordingly, the correlations between SPT N value and G_{max} were evolved. Various standard correlations between SPT N values-Vs proposed by different researchers for various types of soils are listed in Table 3.

Table 4 shows the correlations developed for six set of soils under three different earthquake motions and with the combined dataset of these three earthquakes. The correlation coefficient reduced in each soil types when the combined dataset of three earthquakes used for evolvement of correlations. In regular soils/rocks such as silt/sandy silt, clay, and sand stone, the deviation in correlation coefficient (R^2) is less as compared to complex soils such as clay mix with pebbles-gravel-boulder, boulder mix with clay/sand matrix, and boulder conglomerate. The borehole data is scattered over an area of 1118 square kilometres, and the borehole profiles are not uniform. The soil strata is highly layered resulting deviations in the response of each bore profile. In complex soils such as boulder conglomerate, the pebbles and boulders are embedded in cementitious material like seeds in watermelon. Shear modulus is governed by quantum of cobbles/pebbles and boulders as well as their spatial distribution. The deviations are large resulting in poor correlation coefficient due to non-homogeneity of soil strata and density variation with depth in this studied area. The existing literature shows hardly any correlations for similar strata. Table 5 shows some existing correlations developed by various researchers.

Table 4. Proposed correlations between SPT N and G_{max}.

Sr. No.	Soil Type	Correlation between G_{max} and SPT-N			
		El Centro EQ (M_w = 6.9)	Loma Prieta EQ (M_w = 7.0)	Petrolia EQ (M_w = 7.2)	Combined for all earthquakes
1	Medium grained saturated sandy silt/ silt	$G_{max} = 1.8153\ N^{1.1094}$ $R^2 = 0.9158$	$G_{max} = 6.1059\ N^{0.8797}$ $R^2 = 0.952$	$G_{max}=2.6791N^{0.9657}$ $R^2 = 0.9052$	$G_{max} = 3.0967\ N^{0.9849}$ $R^2 = 0.802$
2	Clay	$G_{max} = 5.2212\ N^{0.8678}$ $R^2 = 0.9372$	$G_{max} = 9.1051\ N^{0.7854}$ $R^2 = 0.9467$	$G_{max} = 5.7259\ N^{0.8154}$ $R^2 = 0.9375$	$G_{max} = 6.4809\ N^{0.8229}$ $R^2 = 0.8791$
3	Sand stone	$G_{max} = 7.2949\ N^{0.8454}$ $R^2 = 0.9497$	$G_{max} = 13.516\ N^{0.7068}$ $R^2 = 0.6666$	$G_{max} = 7.5132\ N^{0.8338}$ $R^2 = 0.9535$	$G_{max}= 9.0482N^{0.7953}$ $R^2 = 0.8477$
4	Boulder/ boulder with sand/ clay/ sandy matrix	$G_{max} = 3.4183\ N^{0.7391}$ $R^2 = 0.5192$	$G_{max} = 47.451\ N^{0.3591}$ $R^2 = 0.6118$	$G_{max} = 5.513\ N^{0.5878}$ $R^2 = 0.3341$	$G_{max} = 5.2897\ N^{0.6582}$ $R^2 = 0.4166$
5	Clay with sand, pebbles, cobble and boulders	$G_{max} = 0.0183\ N^{2.0345}$ $R^2 = 0.7932$	$G_{max} = 3.9504\ N^{0.8473}$ $R^2 = 0.9055$	$G_{max} = 0.016\ N^{1.9273}$ $R^2 = 0.5889$	$G_{max} = 0.1071\ N^{1.5992}$ $R^2 = 0.5073$
6	Boulder conglomerate/ boulder conglomerate with sandy matrix/boulder conglomerate with clay matrix	$G_{max} = 5.6909\ N^{0.6486}$ $R^2 = 0.6988$	$G_{max} = 8.9524\ N^{0.6239}$ $R^2 = 0.8277$	$G_{max}= 15.711\ ^{N}0.3513$ $R^2 = 0.3515$	$G_{max} = 9.2847\ N^{0.5413}$ $R^2 = 0.4338$

Table 5. Some existing correlations between G_{max} and SPT-N.

Authors	G_{max} (MPa)	Soil type
Ohba and Toriumi [43]	$11.96\ N^{0.62}$	Alluvial sand, clay
Imai and Yoshimura [44]	$9.81\ N^{0.78}$	Mixed soil type
Ohsaki and Iwasaki [46]	$11.94\ N^{0.78}$	All soil type
Ohsaki and Iwasaki [46]	$6.374\ N^{0.94}$	Sandy soil
Ohsaki and Iwasaki [46]	$11.59\ N^{0.76}$	Intermediate soil
Ohsaki and Iwasaki [46]	$13.73\ N^{0.71}$	Cohesive soil
Ohsaki and Iwasaki [46]	$11.77\ N^{0.80}$	All soil types
Hara et al. [65]	$15.52\ N^{0.668}$	Alluvial, diluvial and tertiary deposit
Ohta et al. [66]	$13.63\ N^{0.72}$	Tertiary soil, diluvial sandy and cohesive soil
Imai and Tonouchi [50]	$17.26\ N^{0.607}$	Alluvial clay
Imai and Tonouchi [50]	$12.26\ N^{0.611}$	Alluvial sand
Imai and Tonouchi [50]	$24.61\ N^{0.555}$	Diluvial clay
Imai and Tonouchi [50]	$17.36\ N^{0.631}$	Diluvial sand
Imai and Tonouchi [50]	$14.12\ N^{0.68}$	All soils type
Anbazhagan and Sitharam [67]	$24.28\ N^{0.55}$	Silty sand with less percentage of clay
Kramer [38]	$15.56\ (N60)^{0.58}$	Sandy soil

Imai and Yoshimura [44] developed the very first correlation between G and SPT-N values by taking shear wave velocity measurements in various soil layers with down hole method and assuming the same value of unit weight for all soil layers for calculation of shear modulus. Ohba and Toriumi [43] also gave the correlation based on their experimental study at Osaka and assuming the same value of unit weight for all soil layers. Ohta et al. [64] have presented the correlation for shear modulus using 100 sets of data from 18 locations, and the authors observed that the cohesive soils have a little higher shear modulus than the sandy soils for the same values of N but the difference was not so definitive. Ohsaki and Iwasaki [46] have highlighted that the correlation obtained for cohesive soils is well-correlated, and those for intermediate soils are fairly correlated since soils of too much variety are incorporated in this category.

Imai and Tonouchi [50] developed correlations between SPT-N with shear wave velocity and shear modulus from the dataset that consists of 400 boreholes and measured shear wave velocities. Average N values for single velocity layer considered. The dataset includes alluvial peat, clay, sand and gravel, diluvial clay, sand and gravel, tertiary clay and sand, fill clay and sand, and special soil of loam and Sirasu.

In general, the existing correlations except those developed by Imai and Yoshimura [44], the remaining equations were developed assuming SPT-N values less than 1 and extrapolating SPT N values more than 50 using measured shear wave velocity. Anbazhagan and Sitharam [65] developed a correlation between measured SPT-N and shear modulus values using the data generated for seismic microzonation study of Bangalore, India.

The above discussion indicates that the correlations developed for complex soils containing clay mix with pebbles-gravel-boulder, boulder mix with clay/sand matrix and boulder conglomerate and fractured strata will be useful for obtaining shear modulus values.

3.2. Applications of present work

The amplification factors presented in the study provide a clear information about the amplification of input motion of an earthquake having particular characteristics in various sub-divisions of the Hamirpur district. The information will be of utmost importance while planning and design important structures enabling the planners to exclude the areas having larger amplification of motion.

The proposed correlations between standard penetration resistance value N and shear modulus G will be helpful in planning and designing of important structures located in the studied area in the sub-Himalayan zone with non-linear soil strata having variable density with depth. The use of correlations will be economical since exhaustive field-testing will not be required particularly for evolving the preliminary designs.

4. Conclusions

1. The input time history of the earthquakes affects the amplification of different soils differently. Ground motion amplification is seen more in soft regular soils such as clay because of damping effect, whereas in combined soils such as clay mixed with pebbles-gravels-boulders, and boulders conglomerate, amplification is less. Also in a regular hard soil such as sandstone, amplification is less.
2. The correlation coefficient evolved for regular soils is 0.73 to 0.97, which is in coherence with the existing correlations in the literature. However, the shear modulus correlations for complex soils exhibit weaker correlation coefficients indicating the scatter of the nature of soils, the quantum of the constituents, and their spatial distribution along the depth.
3. In complex soils like boulder conglomerate, the pebbles/cobbles and boulders are embedded in cementitious material like seeds in watermelon and in such soils, shear modulus, and input motion amplification is governed by the quantum of cobbles/pebbles and boulders and their spatial distribution. The deviations in the response are large resulting in poor correlation coefficient, i.e. 0.47 to 0.52 in the present case. Input motion amplification is governed by quantum of cobbles/pebbles and boulders and their spatial distribution.
4. The study reveals that the site response parameters and shear modulus correlations for the hilly terrain comprising of highly complex geological formations such as mixed soil and fractured rocks exhibit poor correlation coefficient. For other soils, correlations developed in the present study are matching.
5. The soft soils amplify input motions relatively more than hard soils depending upon their constituents. In Bhoranj and Barsar sub-divisions with soil profile having clay as predominant constituent, amplification factor varies from 1.35 to 2.64 and 1.10 to 2.57, respectively, whereas in other sub-divisions Hamirpur, Sujanpur, and Nadaun with soil profile containing boulders, conglomerate, and boulders mixed with clay, sand stone and conglomerate with sandy matrix wherein the amplification factor varies from 1.29 to 2.34.

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تجزیه و تحلیل پاسخ سایت و همبستگی تجربی بین مقادیر N و مدول برشی برای منطقه زیر هیمالیا حمیرپور با استفاده از ProShake

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چکیده:

در کار حاضر، همبستگی‌های تجربی بین مقادیر N تست نفوذ استاندارد (SPT) در مقابل مدول برشی (GMAX) و تقویت‌های پیک شتاب زمین (PGA) برای ناحیه زیر هیمالیا-هامیرپور، هیماچال پرادش (هند) متشکل از متغیرهای بسیارشامل متغیر لایه های خاک/سنگ در اعماق مختلف و در سراسر زمین ارزیابی شد. در مرحله اول، مقادیر N به‌دست‌آمده از SPTS در ۱۸۴ مکان که منطقه مورد مطالعه را پوشش می‌دهند، به صورت میدانی انجام شد. سرعت موج برشی برای هر پروفیل خاک در هر گمانه با استفاده از بهترین همبستگی موجود در پیشینه‌ی پژوهش محاسبه شد. علاوه بر این، پارامترهای پاسخ لرزه‌ای برای این مقادیر با استفاده از نرم افزار PRO-SHAKE ارزیابی شد. در نهایت، روابط تجربی بین حداکثر مدول برشی و مقدار SPT برای انواع مختلف خاک همراه با تقویت حرکت زمین تعیین می‌شود. ضریب تقویت برای زیربخش بورانج از ۱/۴ تا ۲/۶ و از ۱/۲۸ تا ۲/۳، ۱/۲ تا ۲/۱، ۱/۲۲ تا ۱/۸۵ و ۱/۲۲ تا ۱/۷ برای برسار، نادان، حمیرپور و سوجانپور به ترتیب متغیر است. منطقه مورد مطالعه شامل لایه‌های خاکی متغیر شامل خاک رس، سیلت، ماسه، کنگلومرا، ماسه سنگ و مخلوط آنها است. همبستگی بین مدول برشی و مقدار N با همبستگی‌های گزارش شده قبلی برای خاک‌های معمولی منسجم است. ضریب تقویت گزارش شده برای سایت ها نقش مهمی در برنامه ریزی زیرساخت در منطقه ایفا می کند. همبستگی بین حداکثر مدول برشی (GMAX) و مقدار SPT برای زمین‌های تپه‌ای متشکل از سازندهای زمین‌شناسی بسیار پیچیده مانند خاک مخلوط و سنگ‌های شکسته ارائه‌شده در این مطالعه، در کار تحقیقاتی انجام‌شده قبلی در دسترس نیست.

کلمات کلیدی: مدول برشی، تست نفوذ استاندارد، سرعت موج برشی، اوج شتاب زمین، ضریب تقویت.