Development and Validation of Shear Wave Velocity (V_s^{30}) Map of Pakistan Using the Slope-Derived Method

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I certify that this research work titled "*Development and Validation of Shear Wave Velocity (V_s^{30}) Map of Pakistan using the Slope-Derived Method*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Copyright Statement

Acknowledgements

All the glory and thanks to Almighty Allah, the most Gracious. The most bountiful, who through his divine book always motivates us to get His unlimited Grace. All the admiration to our dear holy prophet Muhammad (S.A.W) who after a lot of hardships and difficulties, made us able to recognize our Allah and who distinguish virtue and evil.

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Abstract

Earthquakes can have intense consequences on any societies and their surrounding structures. Furthermore, ground motions amplified by surficial materials can intensify the situation, often making the difference between minor and major damage. Classification of sites by shear-wave velocity has become more common; the shear wave velocity of soil and rock is one of the key components in establishing the design response spectra, and therefore the seismic design forces, for a building, bridge, or other structure. The method has been proposed for evaluating global seismic site conditions, or the average shear velocity to 30 m depth (V_s^{30}), from the Shuttle Radar Topography Mission (SRTM) 30 arc-sec digital elevation models (DEMs). The basic principle of the method is that the topographic slope can be used as a reliable proxy for V_s^{30} in the absence of geologically and geotechnical based site-condition maps through correlations between V_s^{30} measurements and topographic gradient. However, to validate the data based on available geological map of Pakistan, the results extracted from the proxy-based method are then compare with the classification of area based on strata/soil present in the area and the measured V_s^{30} values. This study collected high quality geotechnical investigation reports with standard penetration test (SPT) N-values. While the proxy-based V_s^{30} map is developed using a correlation between V_s^{30} and topographic slopes for active tectonic regions. From slope derived V_s^{30}map of Pakistan, the major area of both Punjab and Sind provinces has stiff soil, areas of Sind alongside with the sea have soft loam, and the different parts of both Khyber Pakhtunkhwa and Baluchistan are rocky, very dense, soft, and stiff soil. Northern areas of Pakistan are mountainous; therefore, it has higher values of V_s^{30}. The highest V_s^{30} values in the Northern areas are estimated from hard rocks, including porphyritic granite-granodiorite, augen flaser gneisses, tourmaline granite, and pegmatite in the Mansehra orthogenesis unit. Some areas within the region of Rawalpindi-Islamabad have mix site classified as C and D, dependent on the presence of limited soil settings (e.g., presence of soft clay or liquefiable soil) that cannot be determined solely with VS profiling. The coastal areas of Sind and some areas of Punjab including Muzaffargarh, Layyah, Attock etc. are susceptible to soil liquefaction as Site Class in these areas are mostly D1 and have ability to liquify during earthquake occurrence.

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List of Abbreviations

V_s^{30}	Shear Wave Velocity up to 30m depth.
SRTM	Shuttle Radar Topography Mission
NEHRP	National Earthquake Hazards Reduction Program
SPT	Standard Penetration Test
DEM	Digital Elevation Model
SHA	Seismic Hazard Assessment
SSCM	Seismic Site Characterization Maps
GM	Ground Motion
PBC	Pakistan Building Code

Chapter 1

Introduction

1.1 Background and Problem Statement

Of all the natural hazards, earthquakes are one of the most destructive and disruptive in nature due to their ability to present a serious risk to the life safety of inhabitants and to the economy of a country/region. Globally around 60% of the fatalities from natural disasters are found to be associated with catastrophic earthquakes (Shedlock et.al., 1999). Also, the financial losses due to earthquakes, have been found to be in hundreds of billions of dollars. For example, the recent earthquakes of Tohoku 2011, Christchurch 2011, Sichuan 2008, and Kashmir 2005 resulted into a loss of lives of thousands of human lives while the financial losses were found to be more than $300 billion, $40 billion, $148 billion, and $5 billion, respectively.

The impact of seismic wave to a structure can be intensify or reduce due to properties of the underlying strata or earth. In the past studies, Shear Wave velocity (Vs) has been considered as a tool to investigate the impact of strata beneath the structure due to earthquake waves. For example, hard rock area has higher value of VS causing minor or lesser amplitude to the seismic waves while the area with the soft or loose soil has lower value of VS, but that could result in intense or major amplitude to the earthquake waves in the concerned area. Mexico City (1985) and California (1989) the major earthquakes that occurred in the last century; the intensification of GM resulted in fatal risk to the inhabitants, assets destruction and growth of the states. The intensification of GM of the strata can be utilized in the design and as well as the aftermath of structure in the event of earthquake occurrence. This data can be used as well for the quick response in emergency, catastrophe moderation, and urban development. To account for this site amplification during the seismic design of buildings and structures, building codes and the engineers have depended on the average values of VS through the uppermost 30 meters (m) of the subsurface called as V_s^{30} as a criterion to represent the effects of site amplification. For this purpose, seismic site-conditions maps based on V_s^{30} values have been developed all over the globe (Park and Elrick, 1998; Wills et al., 2000; Holzer et al., 2005). These maps help to identify the site amplification at any site of interest. To make these maps more meaningful for the design engineers, the V_s^{30} values have been divided into different ranges and each range represents a particular soil type ranging from a Type A (hard rock) to Type F (soft clay).

Similar classification has been adopted by different building codes i.e., Uniform Building Code (UBC), International Building Code (IBC) and National Earthquake Hazards Reduction Program (NEHRP) (BSSC 2000). Also, the V_s^{30} values are required as an input in the Ground Motion Prediction Equations (formerly called attenuation relationships) (GMPEs) (Boore et al., 1997) and the Next Generation GMPEs (Chiou and Youngs, 2006). In addition, the V_s^{30} values are also used in loss calculations due to earthquakes using earthquake loss models and play a vital role in the earthquake management, i.e., mitigation, preparedness, response, and recovery.

Development of these maps for any region requires a large amount of V_s^{30} data. In majority of seismically active areas across the globe, especially in developing countries like Pakistan, the surficial geological data and V_s^{30} measurements are either not available or if available, they are very limited in number to develop a seismic site-conditions map. Such maps are only available for few seismically active urban areas of the world (e.g., California, Taiwan, Italy, and Japan etc.) as it needs a lot of investment for the geotechnical and geological exploration.

1.2 Problem Statement

The local soil may significantly amplify the ground motion experienced by the bedrock. This amplification effect is quantified using the ground response analysis. The primary input required for the ground response analysis is the average value of shear wave velocity V_s through the uppermost 30 meters (m) of subsurface. Developing-Nations like Pakistan typically have inadequate data about V_s^{30}. Therefore, structural engineers are not able to determine surface-level seismic hazard. In the absence of experimental data, the use of proxy methods may provide an estimate of V_s values within required degree of accuracy.

1.3 Aims and Objectives

The following objectives are set for this study.

1. To develop the V_s^{30}. map of Pakistan using a slope-derived method.
   - To convert the DEM of Pakistan into topographic slope map.
   - To convert the topographic slopes into V_s^{30} values using the modified active tectonic V_s^{30} correlations given by Wald & Allen (2007).
2. The collection of measured V_s^{30} values and SPT data at different sites in Pakistan.
3. The validation of developed V_s^{30} map of Pakistan by comparing the slope-derived values with experimental values obtained for different sites in Pakistan.

1.4 Scope and Limitations

The impact of seismic wave to a structure can amplify or de-amplify due to properties of the underlying strata. In this study the whole region of Pakistan Including AJK and Northern areas were considered for developing the V_s^{30} Map of Pakistan. From this study, structural engineers would be able to determine the site class and surface-level seismic hazard at any location in Pakistan as per Building Code of Pakistan.

As the available data of directly measured shear wave velocity in Pakistan is very limited and the geotechnical investigation in Baluchistan is inadequate as well, so the proxy-based V_s^{30} in those area may fluctuate to the on-site V_s^{30} value, but its variation would be in same site class.

1.5 Outline of Thesis

The report has been organized in following outlines.

Chapter 1: General introduction about the shear wave velocity

Chapter 2: Contains a brief description about the literature review and the already work done in this space.

Chapter 3: Development of V_s^{30} Map of Pakistan

Chapter 4: Contains Analysis their Results and discussion about the results.

Chapter 5: The conclusion drawn from this research work and recommendations for future studies.

Chapter 2

Literature Review

This chapter presents literature review of the main objectives of the current study as defined in Chapter 1. Section 2.1 describes the review of seismic hazard assessment (SHA) of Pakistan, Section 2.2 explains the review of the influence of site-condition on SHA of Pakistan, Section 2.3 enlightens the review of seismic hazard map based on Geology and Shear-wave Velocity of Rawalpindi-Islamabad, Pakistan. Section 2.4 explains the review of developed V_s^{30} maps based on Geology for a case study in Northern Areas of Pakistan, Section 2.5 describes the review of correlations between V_s^{30} and SPT- N Values, Section 2.6 describes the Wald and Allen (2007) proxy-based method for developing V_s^{30}map using topographical slope and Section 2.7 present the summary of this chapter.

2.1 Review of Seismic Hazard Assessment of Pakistan

Throughout the World, earthquakes are common and will continue if the tectonic movement lasts. These earthquakes have produced severe danger to the built structures and setups by intense ground movements and earthquake-induced landslides, surface faulting, tsunamis etc. To minimize the risk to the life safety, structures, economy, and advancement of a region/country due to earthquakes; reliable seismic hazard is necessary. Pakistan is an earthquake prone country and has a long history of earthquake hazards/disasters. Several studies have been done in the past for the SHA and seismic zonation of Pakistan starting from

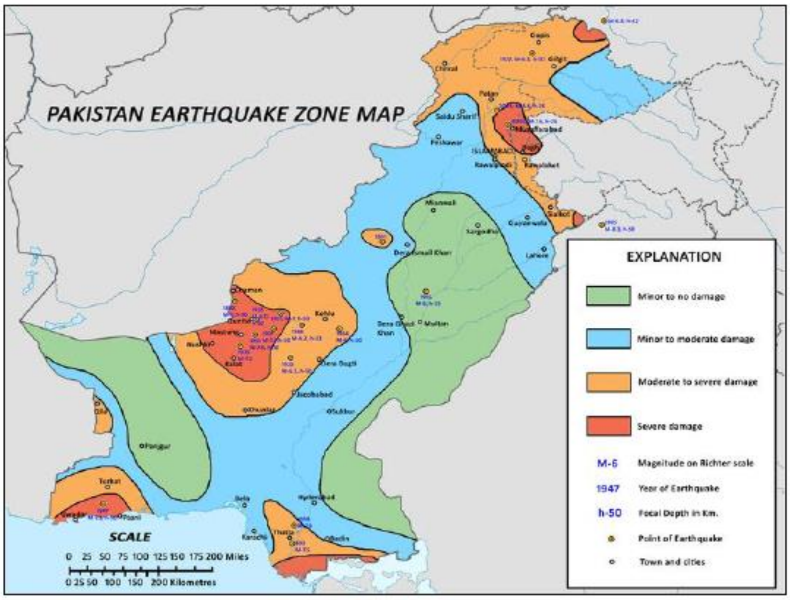


Fig 2-1 Seismic Hazard Zone Map of Pakistan (NESPAK 2007)

Geological Survey of Pakistan (GSP) study in 1974 to a recent assessment study by National Engineering Services of Pakistan in 2007 (NESPAK 2007).

In 1974, the GSP prepared earthquake risk zonation map of Pakistan for the first time. It consists of seven (7) zones with g‘values ranging from less than 0.01g to 0.31g. In this map, a small eastern part, that also includes Islamabad, depicts values of 0.2g to 0.3g whereas the western part exhibits lower values ranging from 0.05g to 0.07g. The study area was dominantly represented by values of 0.07g to 0.15g. The method by which this research was carried out is not clear.

Ghalib (1985) prepared peak ground acceleration (PGA) and peak ground velocity (PGV) contour maps of Pakistan for the return period of 100 and 200 years. The ground motion prediction equations (GMPEs) of McGuire (1977) and Oliveira (1975) were used in the calculation of PGA and PGV. PGA values for 100 years return period were found to be in the range of 0.04g to 0.2g. The method by which this research was carried out is not clear.

In 1986, based on UBC (1982) PBC was developed by the Federal Ministry of Housing and Works. Pakistan was classified into four seismic zones which was based on the instrumental earthquake data (1905 to 1979); the values of observed magnitude in each area during past earthquakes. Zone 0, 1, 2, and 3 represented Negligible damage (MMI ≤ IV), Minor damage (MMI = V to VI), Moderate damage (MMI = VII), and Major damage (MMI ≥ VII), respectively (MMI is Modified Mercalli Intensity). The seismic hazard zoning map was established on a hypothesis that the ground motion of a certain intensity experienced once in a certain area is likely to occur again in that area without considering its recurrence interval.

The Uniform Building Code in 1997 (UBC 1997) assigned seismic hazard zonation for many cities all around the globe/world. For each of these seismic hazard zones, a seismic zone factor is provided which corresponds to PGA for a return period of 475 years (bedrock site conditions).

The Geophysical Center of Pakistan Meteorological Department (PMD) Quetta issued seismic zoning map of Pakistan developed in 1999. The map divides Pakistan into four main seismic hazard zones in terms of major, moderate, minor, and negligible zones with corresponding ground acceleration (g) values. The ground acceleration is in Gal (1g = 981 Gal). In 2006, GSP developed a seismic hazard zonation map of Pakistan based on (a) historical and available earthquake data with magnitude greater than 6.0 and (b) available record of intensities of earthquake events observed in various parts of the country (Ahmed et al., 2006). Pakistan was divided into four seismic zones: zone of no damage, minor damage, moderate damage, and major damage. Each zone have a factor of _g‘which gives the amount of maximum shaking or induced acceleration within or immediately outside that zone due to earthquakes at the site.

Although all the above reviewed seismic hazard assessment studies in the preceding paragraphs in this section provide a platform of awareness about seismic hazard of the region to the community, they were mainly based on either felt intensities of the past earthquakes and/or UBC codes. Also, in some cases, the methodology adopted to carry out SHA of Pakistan was not clear.

The results obtained from these studies (e.g., GSHAP; PMD-NORSAR 2007; NESPAK 2007) were presented in the form of probabilistic seismic hazard assessment (PSHA) maps showing PGA values with 10% PE in 50 years. The Peak Ground Acceleration values estimated from the GSHAP color contour map for major cities—Karachi, Islamabad, Lahore, Peshawar, and Quetta—vary from 0.12g to 0.40g. The PGA values from PMD-NORSAR study are quite like, but generally higher than, those of GSHAP. Comparing to GSHAP and PMD-NORSAR studies, the probabilistic PGA values in the NESPAK study for major cities except Karachi are significantly lower. This is somewhat counterintuitive since the NESPAK study considered both area and fault sources while the other two studies considered only area sources.

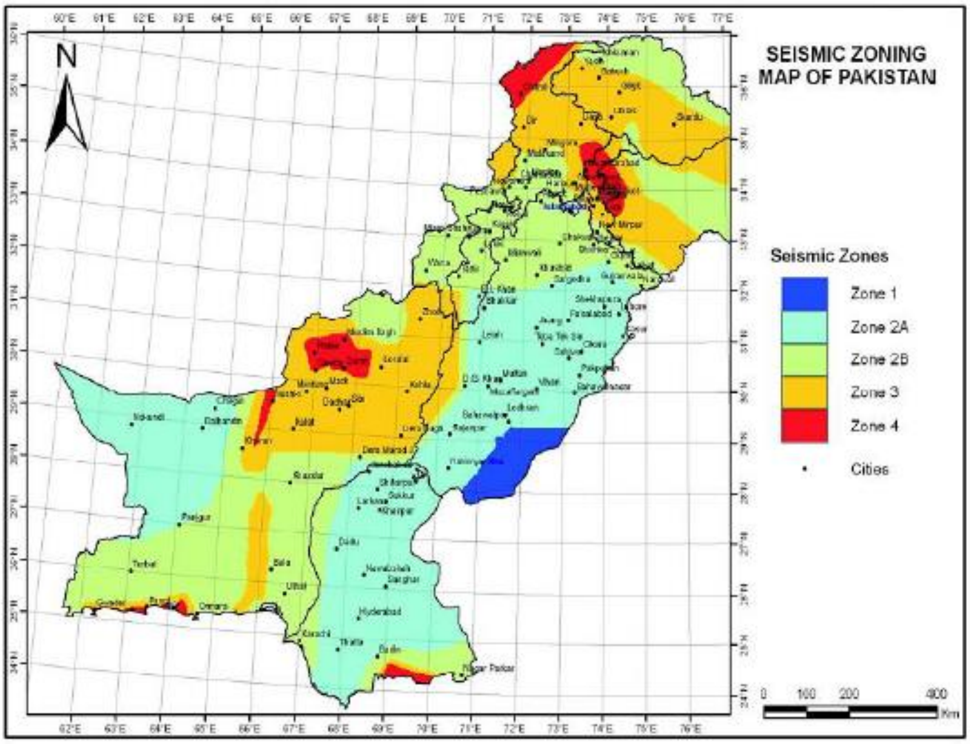


Fig 2-2 Seismic zoning map of Pakistan (NESPAK 2007)

2.2 Review of Influence of Site-Conditions on Seismic Hazard Assessment of Pakistan

Site-conditions provide information about the properties of the underlying site material i.e., bedrock site, soft sedimentary basin, etc. It has an important effect on the amplification and de-amplification of seismic waves (primary-P and shear-S waves) generated during earthquake. If it is bedrock, the amplification is very less while in case of soft sediments, the amplification is quite intense. The International Building Code (IBC) specifies the average values of shear wave velocity at the topmost 30 meters of the strata is termed as V_s^{30}; a technique or base for determining Site class. Site classification based on V_s^{30} values implemented by different building codes i.e., (UBC), IBC and (NEHRP) (BSSC 2000), which varies from A (Hard rock) down to F (Loose Soil).

To develop a site-conditions map for any country/area, a huge dataset of V_s^{30} is needed. In developing countries like Pakistan, the V_s^{30} data is either not available or if available, it is not enough to develop site hazard map. Due to non-availability of V_s^{30} data, some proxy methods can be adopted to develop site hazard maps. Wald et al., (2007) proposed a simple technique using correlation b/w the DEM's slope and the V_s^{30}. In this study, V_s^{30} map of Pakistan has been produced by using Wald 's technique (Wald, 2007).

It is important to note here that the past PSHA studies for Pakistan did not consider the effect of site-conditions on PSHA maps. PSHA studies except for site-specific are mainly based on a reference site condition that is specified to be the boundary between NEHRP classes B and C (rock site), with an average V_s^{30} value of 760m/s, although the original site-condition may not be the rock site.

2.3 Seismic Hazard Map Based on Geology and Shear-wave Velocity of Rawalpindi-Islamabad, Pakistan

Quittmeyer et al. (1979), divided Pakistan in 15 seismo-tectonic areas. Four of these different areas are in locality of Rawalpindi-Islamabad; i) Hazara Region, ii) Salt range, iii) the Himalayas and iv) the Indus basin. BCP divide these areas into six different seismic range areas based on their earthquake source zones. Khan et al. (2011, 2018) divided the Northern Pakistan into 18 earthquake zones considering the strata characteristics at the site source. Twin cities of Rawalpindi and Islamabad located near th zone 12-13. On the basis of PSHA, these cities have Peak Ground Acceleration of 0.220 g for 475 years return period and counted in Zone-2B of BCP (2007).

Khan and Khan (2016) developed the sediments map for the first-time using H/V for the area using Gurlap sismo-meter and tromino energy and the extracted results from the study were efficient and relatable with the data of CDA bore-hole logs available. In 2018, Khan carried out another study to divide the area into different zones based on the soil strata properties i.e. V_s^{30}, frequency and PGA, and the result extracted from this study were helpful in earthquake resilient designing of structures. Khan et. al 2021, developed the shear wave profile using tha H/V data and collected the geological data from the previous studies of area. the relation b/w the geology of the site and V_s^{30} were developed to estimate the V_s^{30} in the areas where direct values were not available. Rawalpindi-Islamabad seismic hazard map was developed using the NEHRP site classes and the PGA for different return periods as mentioned in the Building Codes.

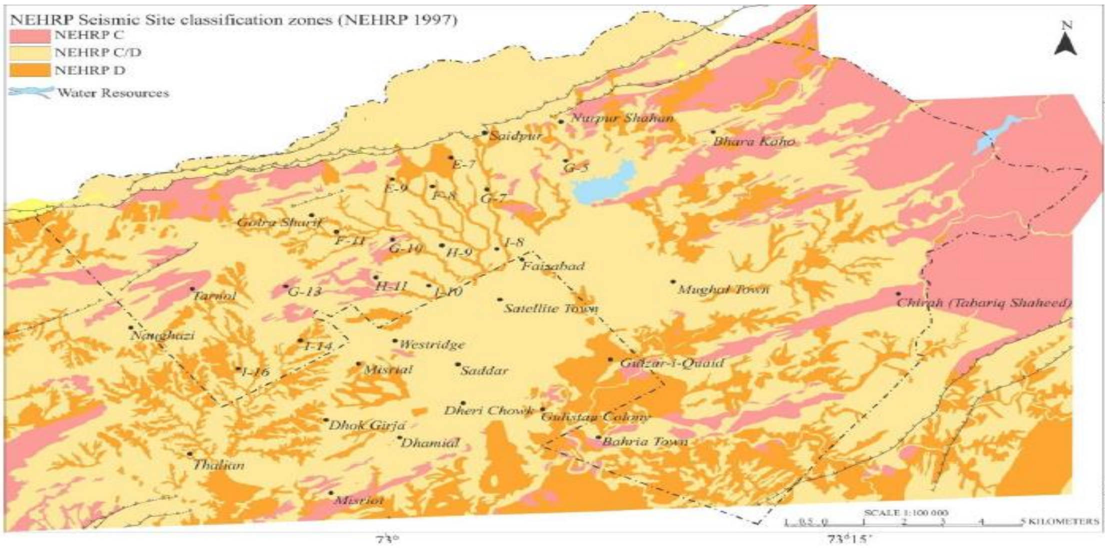


Fig 2-3 NEHRP based site map for Rawalpindi-Islamabad a (Khan et. al 2021)

2.4 Development of Geology Based V_s^{30} Map

Measuring V_s^{30} at a county level practically is not advice-able because of the economical restrictions as it will require huge number of Human Resources as well as equipment needed for the measuring V_s^{30}. Because of these restrictions' geology, some proxy-based techniques based on topography, geology and terrain slope can be used for estimating V_s^{30} at a local scale. Wills et al (2000 and 2006) observed the relation b/w the V_s^{30} and the geology of the area.

Geological unit maps use time of confinement, and the soil sediment size to explain the units. The map is simplified from geologic maps by combining geologic units that are expected to have similar- V_s^{30}. The physical properties that can control the V_s^{30} of any area can vary in between different geologic units; but they donot really define the geological units in any area. Therefore, some geological unit have the same V_s^{30} ranges with different soil properties.. For some classes of units, V_s^{30} values may vary over a relatively small range, and the predicted variation in seismic amplification is small enough that the average V_s^{30} is a useful predictor of amplification on that type of materials. The challenge in preparing a map of shear-wave velocity based on geologic maps is to group those units that have similar velocity.

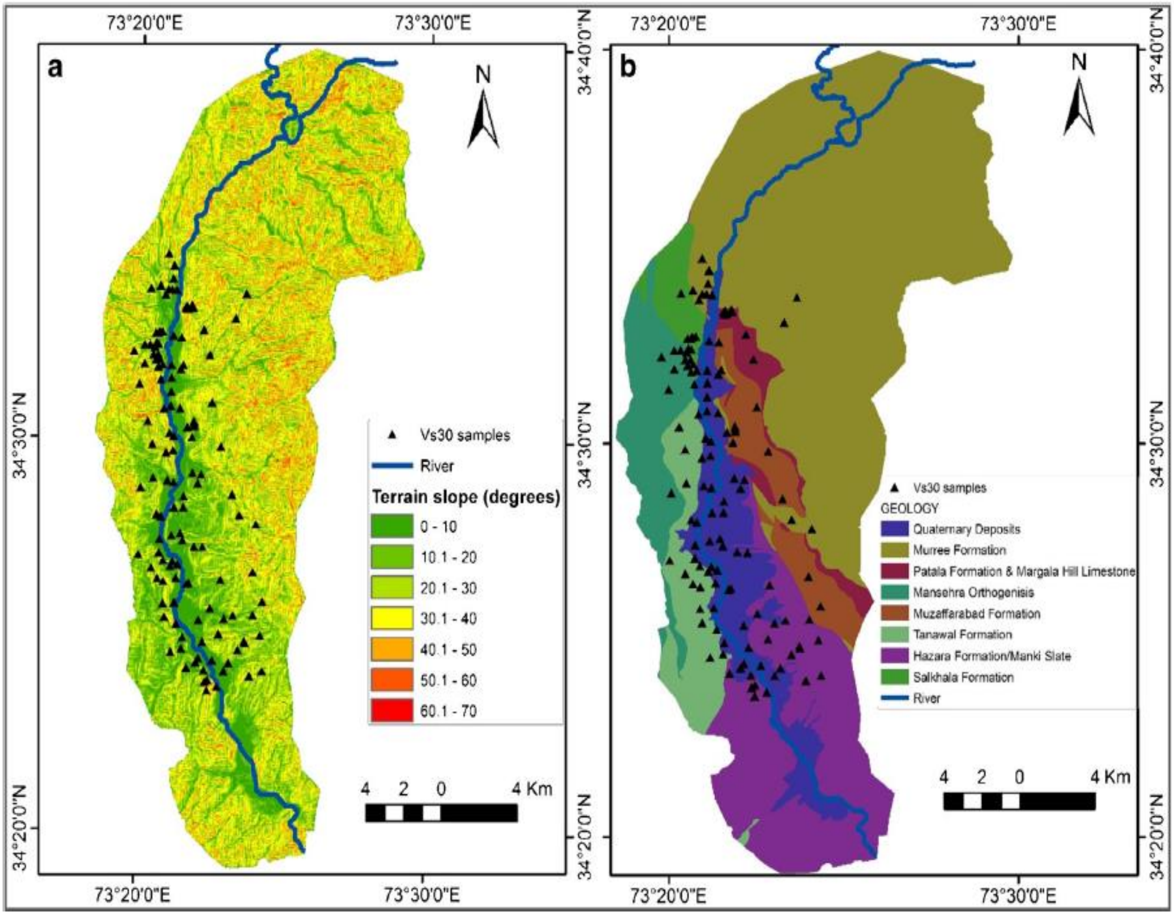


Fig *2*-4(a)Topographical Slope Map and (b) Geological Map for a case study in Northern Area (Waseem et. al 2018)

To estimate the effect of topographical gradient with geological foundations on V_s^{30}; assessed V_s^{30} is compared to topographical gradient and geological unit of the area. The topographical slope from the elevation model of 30-m resolution was computed for the study area. The soil characteristics or strata controls the seismic intensification at the site; presence of the different geology units on the same slope can weaken the relation between the V_s^{30} and the proxy-based techniques

Table 2-1 Geological Units and estimated V_s^{30} as per NEHRP classes. (Waseem et. al 2018)

Geology	**Min- Max** V_s^{30}	**Mean** V_s^{30}	**NEHRP Class**
Mansehra orthogenesis	640–940	837	B
Murree Formation	320–580	446	C
Quaternary deposits	160–430	297	D
Tanawal Formation	480–850	713	C
Patala Formation and Margala Hill limestone	320–770	549	C
Hazara Formation/Manki slate	430–830	696	C
Muzaffarabad Formation	470–650	559	C
Salkhala Formation	510–860	703	C

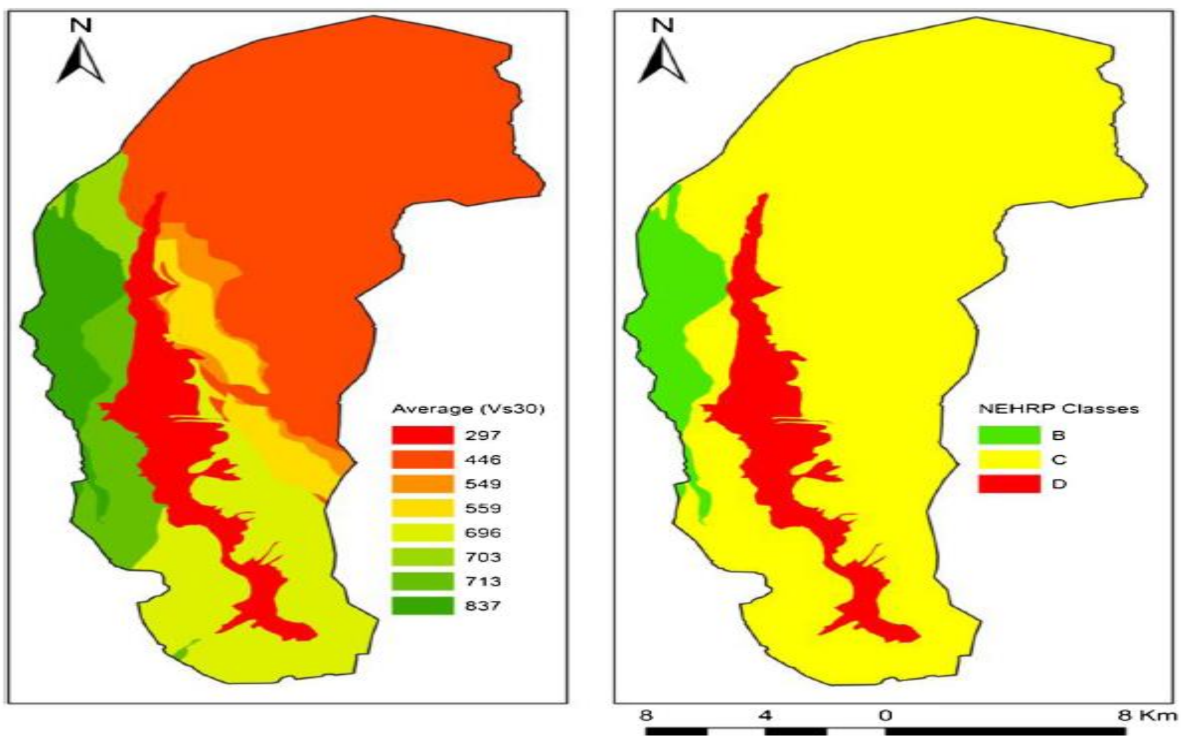


Fig 2-5 V_s^{30}- based seismic site characterization map and Seismic site characterization map according to the NEHRP classes for a case study in Northern Area (Waseem et. al 2018)

The highest V_S^{30} values in the area are assessed for hard rocks. The observed significant influence of the geological formation on the estimated V_S^{30} is in line with the observation of Wills et al. (2015), Yong (2016), and Anne et al. (2012). The mean of estimated V_S^{30} of different geological formations is given in Table 2.1. The mean V_S^{30} of 297 m/s is observed on quaternary deposits, unconsolidated material with fluvial deposits, which was also observed by Wills et al. (2000) and Wills and Clahan (2006).

Table 2-2 Site Classification based on Geologic Units including NEHRP classes (Wills 2000)

Site Class	Geological Unit
B	Plutonic and metamorphic rocks, most volcanic rocks, coarse sedimentary rocks of Cretaceous age and older.
BC	Franciscan Complex rocks except "melange" and serpentine, crystalline rocks of the Transverse Ranges which tend to be more sheared, Cretaceous siltstones, or mudstone.
C	Franciscan melange and serpentine, sedimentary rocks of Oligocene to Cretaceous age, or coarse-grained sedimentary rocks of younger age.
CD	Sedimentary rocks of Miocene and younger age, unless formation is notably coarse grained, Plio-Pleistocene alluvial units, older (Pleistocene) alluvium, some areas of coarse younger alluvium.
D	Younger (Holocene) alluvium.
DE	Fill over bay mud in the San Francisco Bay Area, fine-grained alluvial and estuarine deposits elsewhere along the coast.
E	Bay mud and similar intertidal mud.

The estimated V_S^{30} is, however, significantly controlled by the underlying geology. Hence, the geology of the study area is used as a proxy for a V_S^{30}-based SSCM. The derived V_S^{30}-based seismic site characterization map can be used to formulate strategies for earthquake disaster management in the study area.

2.5 Review of Correlation between V_s^{30} and SPT-N Values

Seismic micro zonation maps have been studied worldwide particularly the seismically active regions. Direct measurement of shear wave velocity in developing countries is not feasible at large scale due to non-availability of funds and expertise in the geotechnical investigations. The use of the available geotechnical data that include SPT-N values and CPT test are used worldwide to calculate the shear wave velocity at any site. Consequently, there are number of correlations were developed all around the globe to predict the V_s^{30} for different types of soils. Amongst variation of soil catalogues, SPT-N values and depth factor are the most used correlation. (Kuo et al, 2011).

Utmost investigators favor to define Vs with the correlation to SPT-N alone (Dikmen, 2009). The contradictory opinion is either should be corrected value of "N" or uncorrected value. Generally, in most of the studies the use of uncorrected SPT-N value was observed while only limited studies focused on the corrected value for generating the empirical correlations. Some researchers had examined the performance for both corrected and uncorrected SPT-N, but different outcomes were obtained.

The effect of soil types has attracted researchers' interest. In general, researchers distinguish correlations for cohesive and cohesionless soils. However, reverse findings exist factually. In fact, these correlations may not be generally and extensively used because soil deposit is a natural product which comprises of various compositions. It is nonlinear and inseparable during boring procedure.

Table 2-3 Correlations between SPT-N values and V_s.

Year	Researcher	Relation	Soil Type
1966	Kanai	**$Vs = 19N^{.6}$**	**All soil**
1970	Ohba and Toriumi	**$Vs = 84N^{.31}$**	**All soil**
1972	Fujimara	**$Vs = 92.1N^{.337}$**	**All soil**
1973	Ohsaki and Iwasaki	**$Vs = 81.47N^{.39}$**	**Cohesionless soil**
1975	Imai and Yoshimura	**$Vs = 92N^{.329}$**	**Cohesionless soil**
1977	Imai	**$Vs = 91N^{.337}$**	**All soil**
1978	Ohta and Goto	**$Vs = 85.35N^{.348}$**	**All soil**
1981	Seed and Idriss	**$Vs = 61.4N^{.5}$**	**Cohesive soil**

1982	Imai and Tonouchi	**$Vs = 97N^{.314}$**	**Cohesionless soil**
1991	Yokota et al	**$Vs = 121N^{.27}$**	**Cohesionless soil**
1992	Kalteziotis et al	**$Vs = 76.2N^{.24}$**	**Cohesionless soil**
1995	Athanasopoulos	**$Vs = 107.6N^{.36}$**	**Cohesionless soil**
1996	Iyisan	**$Vs = 51.5N^{.516}$**	**Cohesive soil**
1997	Jafari et al	**$Vs = 22N^{.85}$**	**Cohesionless soil**
2001	Kiku et al.	**$Vs = 68.3N^{.292}$**	**Cohesive soil**
2008	Lee and Tsai	**$Vs = 137.153N^{.229}$**	**All soil**
2009	Dikmen	**$Vs = 58N^{.39}$**	**All soil**
2010	Uma Maheswari et al.	**$Vs = 95.64N^{.301}$**	**All soil**
2012	Anbazhagan et al	**$Vs = 68.96N^{.51}$**	**All soil**
2013	Marto et al	**$Vs = 93.67N^{.389}$**	**All Soil**

2.6 Wald and Allen (2007) Technique for Site-Condition Map

Due to non-availability of in-situ measured V_s^{30} values; different proxy-based techniques are adopted to produce the hazard maps based on the soil site class. Wald et al., (2007) proposed a method using the correlation b/w the topographical slopes range and the V_s^{30} values. The method rapidly develops a site-condition map for any region based on V_s^{30}; just by computing topographic slope from readily available SRTM Digital Elevation Model.

Wald et al., (2007) developed the site class maps for US, Italy, Taiwan, and Australia and from the results extracted for these countries. They develop a Slope based V_s^{30} parameter for the other countries based on the tectonic setting of the regions (active and stable tectonic regions). These parameters are then further modified by Allen et al., (2009) with modified subclasses.

Table 2-4 Site Class Based on V_s^{30}

Class		**V_s^{30} Range (m/sec)**
E		<180
	D1	180-240
D	D2	240-300
	D3	300-360
	C1	360-490
C	C2	490-620
	C3	620-760
B		>760

The technique is consisted of these steps:

i) Compute the slope from DEM Dataset

ii) Assign the coefficients against the calculated slope based on tectonic regime of area (For Pakistan Modified-Active parameters to be used)

iii) Extract the V_s^{30} values at points using the slope ranges from the first two-steps.

To calculate topographic slopes, Wald et al., (2007) used the ―gradient command of Generic Mapping Tools (GMT) (Wessel and Smith, 1998) which uses centered first differences (i.e., the four directly adjacent pixels are used).

These methods are:

I. 4-Cell Neighboring Method

II. 8-Cell Neighboring Method

III. Sharpnack & Akin‘s Method

DEM Surface Tools for ArcGIS setup a surface of 3x3 cell neighborhood around the processing or center cell and computes the average rate of change in elevation along the horizontal (dz/dx) (i.e. E-W) and vertical (dz/dy) (i.e N-S) directions. The slope value of ‘e’ (center cell) is calculated by Equation 2.1 & 2.2

$$\%slope = \sqrt{\left(\frac{d_z}{d_x}\right)^2 + \left(\frac{d_z}{d_y}\right)^2} \qquad (2.1)$$

$$Degree\ slope = Arctan(\sqrt{\left(\frac{d_z}{d_x}\right)^2 + \left(\frac{d_z}{d_y}\right)^2}) \qquad (2.2)$$

Table 2-5 Slope Ranges for NEHRP V_s^{30} Categories

			Slope Range (m/m)		
Class		V_s^{30} **Range (m/sec)**	**Active Tectonic**	**Modified Active Tectonic**	**Stable Continent**
E		<180	<0.0001	<0.0003	<.00002
	D1	180-240	.0001-0.0022	.0003-.0035	0.00002-.002
D	D2	240-300	0.0022-.0063	.0035-.01	.002-.004
	D3	300-360	.0063-.018	.010-.018	.004-.0072
	C1	360-490	.018-.050	.018-.050	.0072-.013
C	C2	490-620	.050-.10	.050-.10	.013-.018
	C3	620-760	.10-.138	.10-.14	.018-.025
B		>760	>.138	>.14	>.025

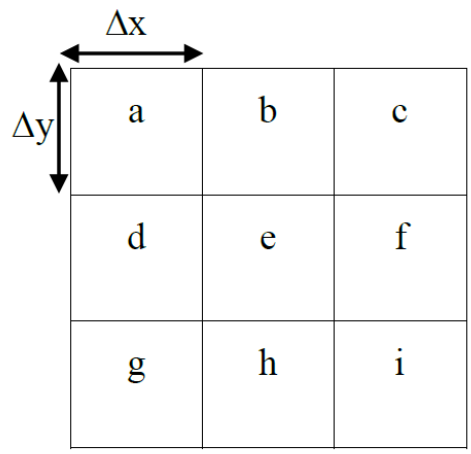


Fig 2-6 3x3 cell arrangement with 'e' as the central cell Δx and Δy are the dimensions of each cell

4-Cell Neighboring Method: In this method dz/dx is computed from the cells immediately east and west of the central cell, and dz/dy is calculated from the cells immediately north and south of the central cell. The dz/dx for cell 'e' and the dz/dy for cell *'e'* is calculated by Equation 2.3 and 2.4,

$$\frac{dz}{dx} = \frac{(-f+d)}{(2*\Delta x)} \tag{2.3}$$

$$\frac{dz}{dy} = \frac{(b-h)}{(2*\Delta y)} \tag{2.4}$$

8-Cell Neighboring Horn 's Method: In this method dz/dx is computed from the difference between the sums of the elevations in the first and third columns of the 3x3 matrix, and dz/dy is calculated from the difference between the sums of elevations in the first and third rows.

In each case the four immediate neighbors are weighted by a factor of two and the rest of four corner cells by one. The dz/dx for cell ‘e’ and The dz/dy for cell ‘e’ is calculated by Equation 2.5 and 2.6, ArcGIS 9.2 Slope tool employs the same method in computing slope i.e. Horn ‘s Method.

$$\frac{dz}{dx} = \frac{(c+2f+i)-(a+2d+g)}{(8*\Delta x)} \quad (2.5)$$

$$\frac{dz}{dy} = \frac{(g+2h+i)-(a+2b+c)}{(8*\Delta y)} \quad (2.6)$$

Sharpnack & Akin‘s Method: In this method dz/dx is computed from the difference between the sums of the elevations in the first and third columns of the 3x3 matrix, and dz/dy is calculated from the difference between the sums of elevations in the first and third rows with all columns and rows weighted equally. The dz/dx for cell ‘e’ and the dz/dy for cell ‘e’ is calculated by Equation 2.7 and 2.8,

$$\frac{dz}{dx} = \frac{(c+f+i)-(a+d+g)}{(6*\Delta x)} \quad (2.7)$$

$$\frac{dz}{dy} = \frac{(g+h+i)-(a+b+c)}{(6*\Delta y)} \quad (2.8)$$

2.7 Summary of Literature Review

From the past available data and studies, it is evident that shear wave velocity up to top 30-m depth commonly termed as V_s^{30} is a critical criterion in designing earthquake-resilient structure at any site. Around the world and specifically in developed countries where the resources for exploring the data of direct measurement of V_s^{30} is available, they have developed the seismic hazard maps of their region based on the directly measured V_s^{30}data. Several V_s^{30} maps based on direct measurement and proxy-based techniques were developed for the countries with the existing data. Proxy-based V_s^{30} maps can predict the site class of any region with great accuracy. Geology and geotechnical investigation of an area can also help in developing the V_s^{30} for any country or region. The V_s^{30} map of Rawalpindi-Islamabad and Northern areas correctly predicted the proxy-based V_s^{30} from geology and the measured V_s^{30} values of the regions, which validate the using of proxy-based technique for predicting the V_s^{30} for any region in Pakistan. Proxy-based technique developed by Wald and Allen in 2007 using topographical elevation is most widely used for predicting the $V_s^{30}$for any region around the globe based on the tectonic settings of the area, whether it is in active tectonic region or stable tectonic region.

Chapter 3

Development of V_s^{30} Map of Pakistan

3.1 Research Methodology

This research intends to follow a certain sequence of steps, techniques and procedure required to accomplish the above mentioned objectives in Chapter 1.

A research methodology as shown in Fig 3.1 below has been developed. The details will be discussed in the subsequent section:

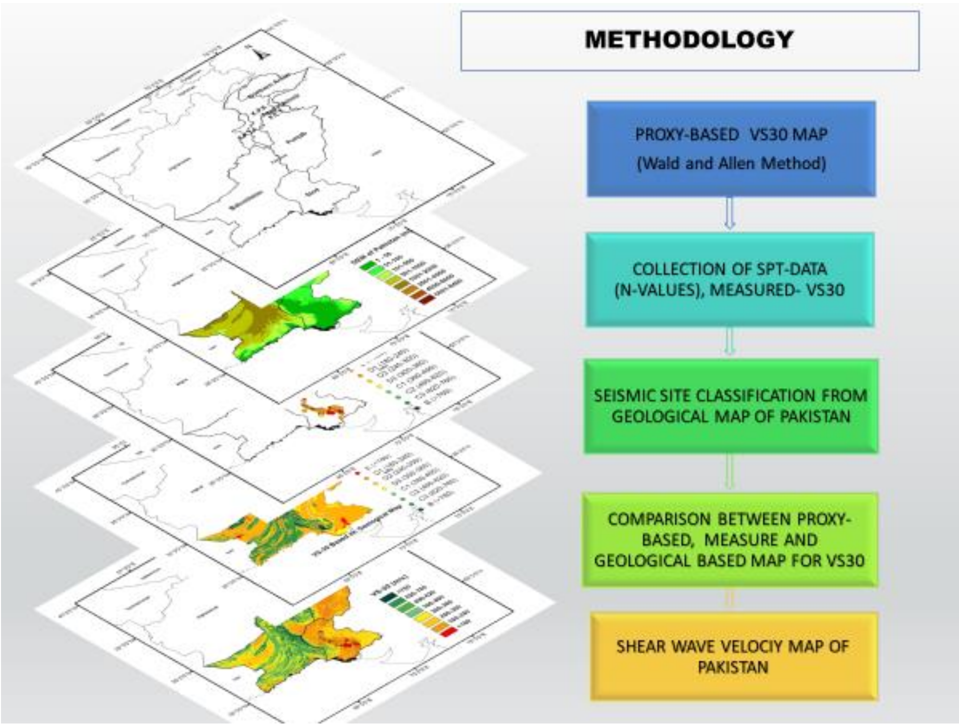


Fig 3-1 Research Methodology

3.2 Wald (2007) Technique and Site-Condition Map for Pakistan

The topographic slopes were computed using the global DEM of the Shuttle Radar Topography Mission SRTM30, which has a 30 arc-sec resolution based on 4-cell method. In the current study, larger resolution SRTM30 DEM (i.e., spatial resolution around 1 km) is used to derive the topographic slopes.

It is also important to note that slopes derived from DEMs with different resolutions will vary in proposed new slope ranges for the classification of sites using these DEM. Wald and Allen (2009) concluded that the maps derived from the higher resolution DEMs lead to finer site classification but gives noisier slope computation. Also, they did not find improvement in the results when compared with the (larger resolution) 30 arc-sec DEM and suggested that the SRTM30 could provide more stable V_s^{30} estimates. In the current study, larger resolution SRTM30 DEM (i.e., spatial resolution around 1 km) is used to derive the topographic slopes. It is also important to note that slopes derived from DEMs with different resolutions will vary in values and may require new correlations with V_s^{30} (Wald et al., 2007).

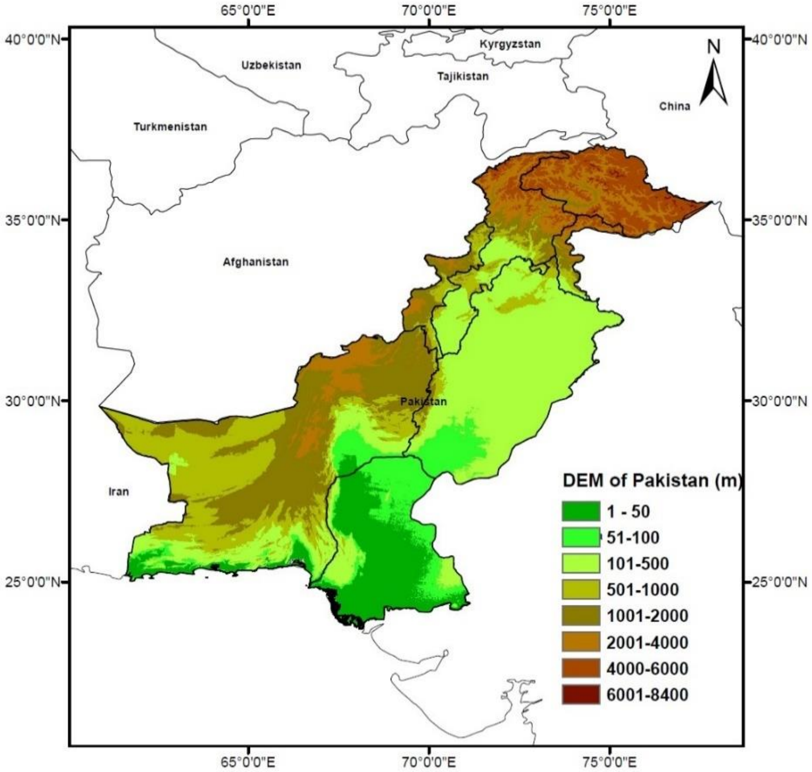


Fig 3-2 Topographical/DEM Model of Pakistan

To derive the first-order site-condition map of Pakistan, the topographic slopes were computed from the DEM of the SRTM30 arc-seconds global topographic data set (Farr and Kobrick, 2000). It is a Near-Global DEM with spatial resolution of approximately 1 km (30 arc-seconds) assembled from the SRTM, and the United State Geological Survey (USGS) GTOPO30 data set. Based on the SRTM30 Data set, the topographic elevation in Pakistan varies from 1 to 8200 m. Most of the south western, western, and northern parts of Pakistan comprise of sedimentary basin and mountains and are at high elevation (1500 -8200 m) while most of the south eastern and eastern parts of Pakistan are basin and plains and are at low elevation (1-1000 m). Khyber Pakhtunkhwa (KPK) and Baluchistan provinces cover northern, western, and south western parts of Pakistan whereas Sind and Punjab provinces cover southern, south eastern, and eastern parts of Pakistan. The elevation of the capital of Pakistan, Islamabad is about 400-1000 m. Following the methods and steps explained in above, first-order site-condition map of Pakistan is generated. It is clear from the slope derived V_s^{30} map that the major areas of both Sind and Punjab provinces have a Site class *D (D1, D2*, and *D3*). The Site class in both KPK and Baluchistan provinces varies in the range of *B*, *C (C1, C2,* and *C3*) and *D (D1, D2,* and *D3*). The Site classification of Islamabad varies in the range of *B*, *C (C1, C2*, and *C3*) and *D (D1, D2*, and *D3*).

3.3 Collection of SPT-N Value and Measured V_s^{30} Data

Now, following are some of the studies in which geotechnical data in the form of SPT blow counts or N-value at various locations in Pakistan is available. These N-values at various locations and depths can be used to calculate their corresponding Vs values. Marto et al., (2013) developed an empirical equation for V_s^{30} by integrating twenty-seven (27) published correlations between shear wave velocity and N-values around the world including India, Iran, U.S.A, Japan, Taiwan, Turkey, Greece, South Korea, and others for all soil types.

Yong et al., (2008) used geomorphic units based on remote-sensing data to develop a site characterization map of Islamabad and surrounding areas. They classified the geomorphic units in the area as a mountain, piedmont, and basin terrain assigning the highest V_s^{30} range to mountains (V_s^{30} greater than 500 m/sec), intermediate range to the piedmont (V_s^{30} of 200-600 m/sec) and the lowest velocity range (V_s^{30} less than 300 m/sec) to the Indus river, the Peshawar basin, and the Soan river valleys based on the demonstrated correlations of shear wave velocity ranges in California Ahmad et al., (2011) characterize the soil at the site of Mardan, Pakistan using SPT, Cone Penetration Test (CPT) and cross-hole test. They classified the site as a Site class D (D3) with V_s^{30} of 321 m/sec. Hussain (1996) carried out an electrical resistivity survey to investigate the ground water table at Mansehra and reported the sediment deposition qualitatively. According to their study, the soil at the site is found out to be type D (D2) with V_s^{30} of about 250 m/sec. V_s^{30} measurement for another site in Pakistan is available from Khan (2013) at Shakardarra (SKD) where the V_s^{30} of 414 m/sec classified the site as a Site class C (C1). Mahmood et al., (2014) calculated V_s^{30} based on SPT and characterize the soil at the site of Margalla Tower, Islamabad as a Site class D (D3) with V_s^{30} values ranges from 315 to 350 m/sec. Erduran et al., (2012) present the damage and loss assessment of Quetta and its surroundings due to potential future earthquakes in the region. They also map the soil classification of the Quetta city, according to NEHRP soil classification. They divided Quetta into thirteen (13) zones based on population, soil type, building typology, and socioeconomic conditions. For these thirteen (13) zones, Site class varies from D, C, and B. All these measured V_s^{30} values along with their Site Classes.

Arshid et al., (2013) divided the area in the foot of Margalla hills Islamabad into three Zones A, B & C based on geotechnical characteristics (SPT N-value). Zone-A comprised of areas having SPT N-value < 8, Zone-B having SPT values from 8-15 and Zone-C having SPT N-value > 15. The available SPT N-value up to 10 m depth in each zone is used to compute shear wave velocity. The estimated V_s^{30} values are 282 m/sec for Zone A, 360 m/sec for Zone B and 500 m/sec for Zone C. The V_s^{30} values characterize the Zone A and B as Site class D2 and D3, and Zone C as a Site class C2.

Kamal et al., (2015) divided Faisalabad city in Punjab province into three Zones I, II & III based on geotechnical characteristics (SPT N-value). Zone-I comprised of areas having SPT N-value < 4, Zone-II has SPT values from 5-8 and Zone-III has SPT N-value ranged from 9-15. The SPT N-value is available up to 18 m depth in each zone and is used to compute the shear wave velocity. The estimated V_s^{30} values are 250 m/sec, 289 m/sec and 332 m/sec for Zone I, II and III, respectively which characterize all the sites within these three Zones as a Site class D2 and D3.

Malik et al., (2015) developed soil profiles, which provide ranges of soil properties and SPT-N values at regular intervals for Lahore city. They divided Lahore city in Punjab province into five zones. The SPT N-values for each zone up to 30 m depth available from their study are used to compute V_s^{30}. The V_s^{30} values characterize all the sites within these five zones as a Site class D1 and D2.

NESPAK (2006) carried out the seismic refraction survey in various parts of Northern Areas (NA), AJK and KPK for the site selection of telecommunication towers. P-wave velocity values were obtained because of seismic refraction survey along with the characteristics of subsurface material (depth to bedrock beneath the surface and rock mass properties etc). The depth of the P-wave velocity at various sites varies from 0-13 m. Based on the P-wave velocity values characterize some of the sites as hard rock while some as weathered rock and some sites as composed of shale and sandstone. In hard rock, the S-wave velocity is usually about half of the P-wave velocity. Neidell (1985) reports the VS/VP ratios for shale, sandstone, and limestone to be 0.5, 0.62 and 0.56, respectively. Keeping these ratios in view, the S-wave velocity is calculated from the P-wave velocity for 0 to 13 m. Although this is a crude representation of shear wave velocity, however, one can get some picture of the shear wave velocity for the sites. Based on these shear wave velocity values most of the sites are classified as a Site Class C (C1, C2, and C3) and B.

NESPAK (2019) carried out the geotechnical investigations (SPT N-values) for the construction of Sukkur-Hyderabad Motorway in Sindh Province, Pakistan. The objective of these investigations was to get the foundation design parameters for the piers and piling of bridges and interchanges. The SPT N at 30m depths available from their study are utilized in the shear wave velocity calculations. The estimated V_s^{30} values, ranging from 180 to 360 m/sec, characterize the Sind sites as a Site class D (D1, D2, and D3).

Khan, et. al (2021), developed the Seismic Hazard Map Based on Geology and Shear-wave Velocity of Rawalpindi-Islamabad, Pakistan. In the study shear-wave velocity (VS) profiles obtained through geophysical H/V measurements and geologic map of the region. Those 85 profiles were used in the comparison for Rwp-Isb region. Khan, et. al conclude that due to presence of soft clay or liquefiable soil and lateral spreading, the study region of Rwp-Isb can be classified as hybrid site class C and D.

Faruq, R. H., & Khan, A. H. (2015) carried out a study in Punjab to map the liquefaction suspectable areas of Punjab. In his study he come up with the following results for liquefaction areas in Punja. High liquefiable sands zones in Punjab are identified in Liaqatpur, Bhawalnagar, Muzzafargarh, Layyah and Minchanabad tehsils in southern Punjab. Attock tehsil in northern Punjab. Malikwal, Waziarabad, Bhalwal and Sargodha tehsils in eastern Punjab. Darya Khan tehsil in western Punjab. Medium liquefiable sands zones in Punjab province are as following Marala tehsil in eastern Punjab.

Also, the SPT-N values and geotechnical investigations reports from some reliable private consultancy firms were collected and based on those reports the estimated values of V_s^{30} for different sites at Rawalpindi, Islamabad, Lahore, and some areas of Northern Punjab were calculated.

Chapter 4

Results and Discussions

The present dataset of Pakistan including direct measured shear wave velocity, the values estimated from the soil investigation data like SPT N-values etc., and the values computed from the P-waves velocity. In the current study, these forms of V_s^{30} data is collected and compared with the slope derived map to verify the accuracy of proxy-based technique to be applied in Pakistan. To validate the slope-derived V_s^{30} map, and the measured V_s^{30} a geology-based map of V_s^{30} was also produced from the geological map available from Geological Survey of Pakistan.

4.1 Proxy-Based V_S^{30} Map of Pakistan

Following the procedures and steps described in preceding sections, V_S^{30} map of Pakistan is produced. It is clear from the slope derived V_s^{30} map that the main areas of both Sind and Punjab regions have a Site class *D* . The Site class in both KPK and Baluchistan regions varies in the range of *B*, *C* and *D*. The Site classification of Federal capital lies in the range of *B*, *C* and *D*.

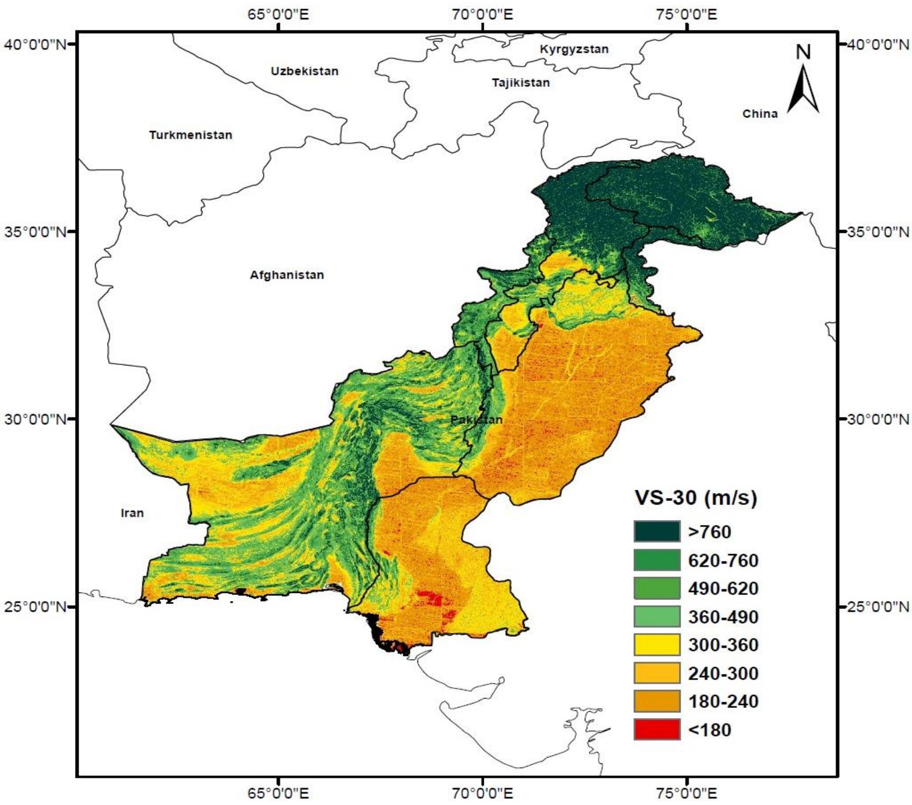


Fig 4-1 Proxy-Based V_s^{30} Map of Pakistan

These are the only few studies from which V_s^{30} measurements in Pakistan are available in the literature.

In the current study, V_s^{30} is computed by using the empirical Equation:

$$\mathbf{Vs = 93.67N^{.389}} \quad (4.1)$$

proposed by Marto et al., (2013) for all soil types. Where "N" is the SPT blow counts. At some locations the N-values are not available up to 30 m depth, therefore extrapolation is needed to estimate the V_s^{30} values. Boore (2004) formulated an extrapolation method (statistical analysis) based on borehole data in California by developing a correlation between the time-averaged VS at the terminal depth of measurement (VSd) and V_s^{30}.

The developed correlation is expressed in the form of an empirical Equation 4.1 as follows:

$$\log(V_s30) = a + b * \log(V_{sd}) \quad (4.2)$$

$$\log(V_s30) = c_o + c_1 \log(V_{sd}) + c_2(\log V_{sd})^2 \quad (4.3)$$

where "a" and "b" are the regression coefficients and their values for different terminal depths. In the current study, VS 30 values are estimated by using Boore (2004) extrapolation method.

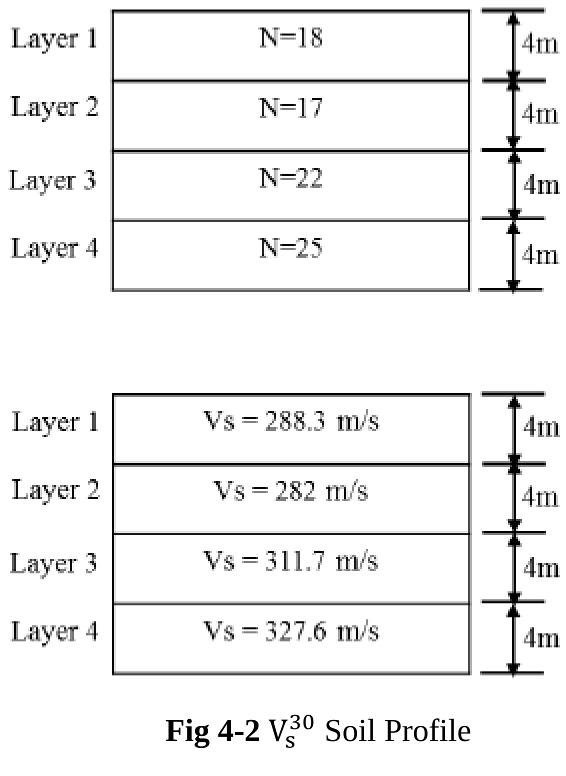


Fig 4-2 V_s^{30} Soil Profile

Following example will illustrate the estimation of V_s^{30} value using SPT N-values. For a soil profile comprises of 1 to n layers each having a SPT N-value and thickness d. For each layer shear wave velocity Vs is computed by using Equation 4.1. After computing Vs for each layer the average V_s^{30} is calculated by using Equation 4.4

$$V_{SH} = \sum_{i=1}^{n} d_i \ / \ \sum_{i=1}^{n} \frac{d_i}{V_{si}} \qquad (4.4)$$

Where Σ , is the thickness of each layer between 0 and 30 m and is the shear wave velocity in m/sec of that particular layer. For example, for a soil profile containing four layers with SPT N-value and thickness d. For each layer shear wave velocity VS is computed by using Equation VS for this soil profile is 16 / (4/288.3 + 4/282 + 4/311.7 + 4/327.6) = 301.34 m/sec. As in this example the N-values are not available up to 30 m depth, therefore extrapolation is needed to estimate the V_s^{30} values. V_s^{30} values are estimated by using Boore (2004) extrapolation method and the regression coefficients given in as:

$$\text{Log } V_s^{30} = 0.013795 + 1.0237 \log (301.34)$$

$$V_s^{30} = 356.21 \text{ m/sec}$$

Following the above example, N-values available at various location in Pakistan are used to compute V_s^{30} values. "Water and Power Development Authority (WAPDA) in 1988 and 1992 carried out geotechnical investigation in the Sind province of Pakistan for Left Bank Outfall Drain (LBOD) surface drainage project" (WAPDA 1988, 1992). The aim of these investigations was to get the geotechnical design parameters for the construction of aqueducts and road bridges in the left bank of Indus delta and coastal zone of Sind. For this purpose, boreholes logs were executed for SPT by Drill Tech Corporation & Mehran University of Engineering and Technology, Jamshoro. The SPT N-values up to 30 m depth available from WAPDA (1988, 1992) are utilized in the current study for the calculation of V_s^{30}. The estimated V_s^{30} values at various sites are in the range of 180 to 360 m/sec i.e., Site class D (D1, D2, and D3). Malik et al., (1992a) carried out detailed subsurface site investigations for the construction of a bridge over the Gambila River on Bannu-Dera Ismail Khan road, KPK. V_s^{30} computed from their SPT N-values are about 360 m/sec i.e. The SPT N-values up to 16.2 m depth available from their study are utilized in the shear wave velocity calculation. The estimated V_s^{30} value is about 240 m/sec i.e. Site class D (D1).

Hayat (2003) carried out a detailed stratigraphic study within the Punjab province to develop geotechnical zonation maps from the surface down to 12.20 m. The SPT N- values up to 12.20 m depth are utilized in the shear wave velocity calculation. The estimated V_s^{30} values using Boore (2004) extrapolation method at various sites are in the range of 180 to 360 m/sec i.e., Site class D (D1, D2, and D3). National Engineering Services of Pakistan (NESPAK) carried out the geotechnical investigations (SPT N-values) in Azad Jammu and Kashmir (AJK) at Barnala site (NESPAK 2006). Their objective was to get the foundation design parameters for the telecommunication towers at the site. The SPT N-values are available up to a depth of 12 m and are utilized in the shear wave velocity calculations. The estimated V_s^{30} value is found to be 348 m/sec i.e., Site class D3.

Table 4- 1 Regression coefficients

Regression Coefficients		Depth (m)
A	***B***	
0.042062	1.0292	10
0.022140	1.0341	11
0.012571	1.0352	12
0.014186	1.0318	13
0.012300	1.0290	14
0.013795	1.0263	15
0.013893	1.0237	16
0.019565	1.0190	17
0.024879	1.0144	18
0.025614	1.0117	19
0.025439	1.0095	20
0.025311	1.0072	21
0.026900	1.0044	22
0.022207	1.0042	23
0.016891	1.0043	24
0.011483	1.0045	25
0.006565	1.0045	26
0.002519	1.0043	27
0.000773	1.0031	28
0.000431	1.0015	29

NESPAK (2007) carried out the geotechnical investigations (SPT N-values) at various sites in the KPK province of Pakistan. The objective of these investigations was to get the foundation design parameters for the telecommunication towers at sites. The SPT N-values at various sites up to a different depth (11-20 m) available from their study are utilized in the shear wave velocity calculations. The estimated V_s^{30} values, ranging from 180 to 360 m/sec, characterize the KPK sites as a Site class D. NESPAK carried out the geotechnical investigations (SPT N-values) at Bannu, KPK province of Pakistan for the construction of Bannu Judicial Complex (BJC) (NESPAK 2011). The SPT N-values up to a depth of 12 m from their subsurface investigations is utilized in the shear wave velocity calculations. The estimated V_s^{30} value of about 400 m/sec, characterize the BJC site as a Site class C1.

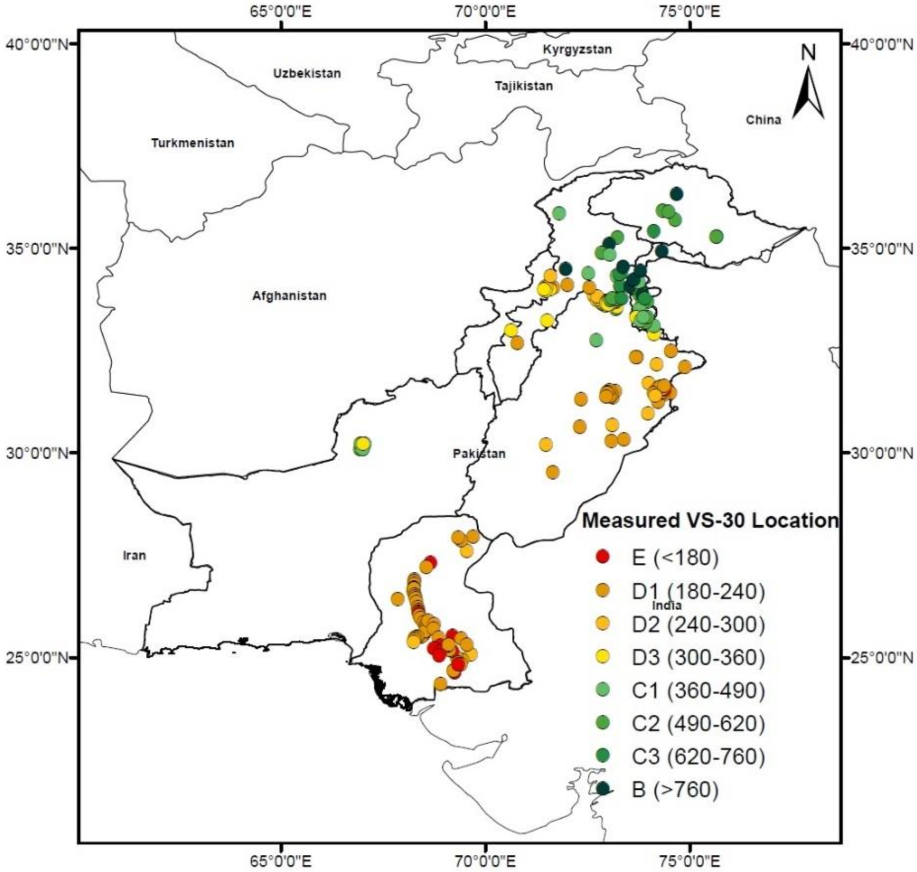


Fig 4-3 Locations of sites with measured V_s^{30} values

4.2 Comparison Of Proxy-Based V_s^{30} Values With Measured V_s^{30} Values In Pakistan

This section explains the comparison of measured V_s^{30} values in Pakistan with the values derived from the site-condition map. The overall comparison between measured V_s^{30} values from the previous literature and reports with the V_s^{30} derived from topographical slope using Wald and Allen method and the V_s^{30} values obtained using the Geological derive V_s^{30} map of Pakistan in the tabular form is attached in Annexure-A (Table A-1). The slope derived V_s^{30} map (for modified active tectonic) of Pakistan exhibits the measured V_s^{30} values (directly available, from SPT N-values and from P-wave velocity values) of 524 different sites at various locations in Pakistan and its comparison with the slope-derived V_s^{30} values. The coded circle highlights V_s^{30} values and their corresponding Site classes. Furthermore, the comparison of the exiting available V_s^{30} maps for some regions of Pakistan with the slope-derived V_s^{30} map is discussed.

In KPK, the available V_s^{30} values at Mardan, Mansehra and Shakardarra. According to the measured V_s^{30} values they are classified as a Site class D3, D2 and C1, respectively. Whereas the Site Class derived from the topographic slope method is D1, C1 and C1 and the geological based site class is CD. At Mansehra, based on measured V_s^{30},Site Class is not matching with the Site Class obtained from the slope-derived V_s^{30} map but geology controls in this area as the site class derived from the geological map and topographic slope is of Site Class C. The Margalla site in Islamabad with directly available V_s^{30} value classify the site as a Site class D same as the Site class obtained from the slope-derived V_s^{30} map and from the previous studies based on geological classification of area.

In Baluchistan, the directly available V_s^{30} values for thirteen (13) zones in Quetta (Erduran et al., 2012) are classified into Site class D, C, and B. The Site classification for these zones derived from the topographic slope method is almost the same, i.e., B, C and D. The available data of SPT-N values in Baluchistan province is very limited in past studies as well as geotechnical investigation reports are also not available. The Geology based V_s^{30}map of Baluchistan is showing an eventful matching with the slope derived V_s^{30} map of the province.

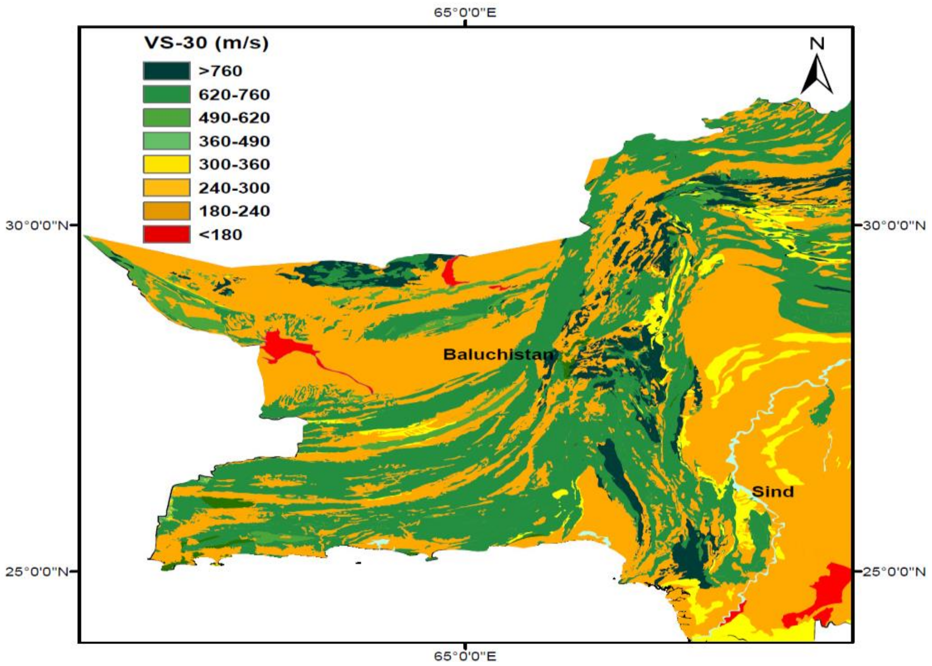


Fig 4- 4 Geology Based V_s^{30}map of Baluchistan

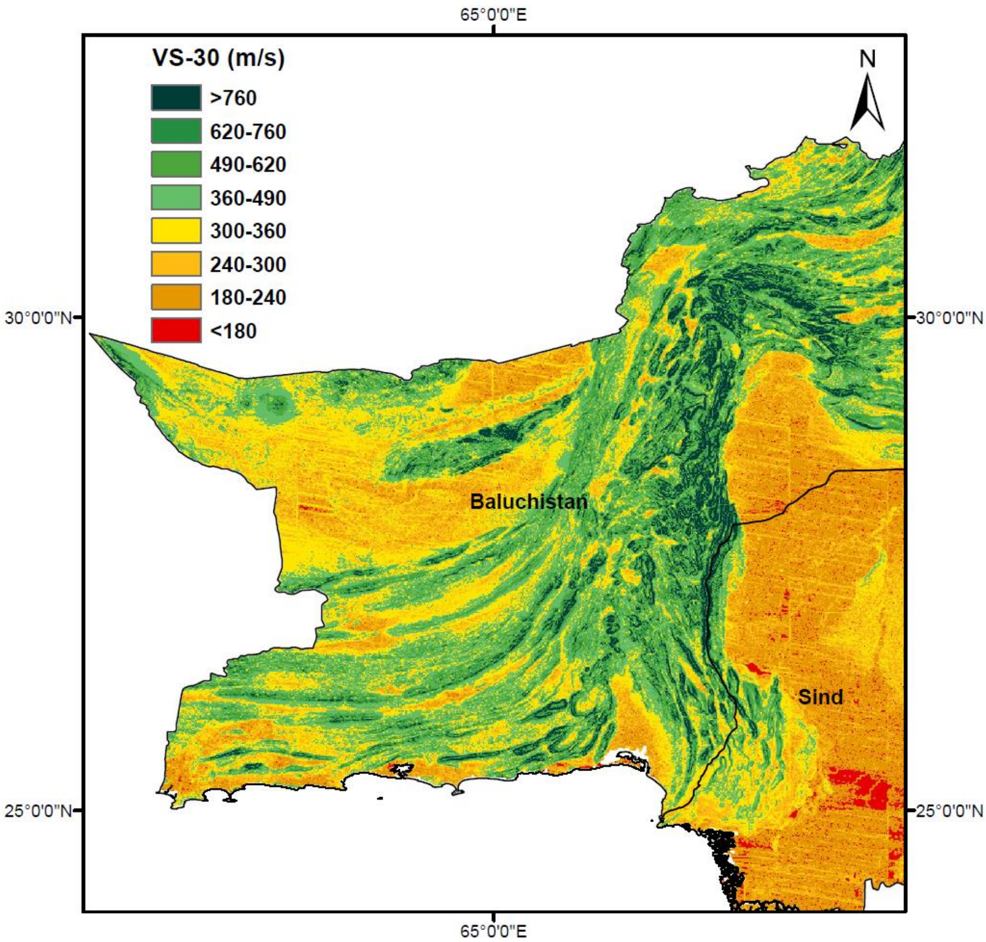


Fig 4- 5 Slope Derived V_s^{30}map of Baluchistan

In Sind, V_s^{30} values for different sites are measured based on SPT-N values available from previous studies. Most of the sites are classified as a Site class D1 based on the measured V_s^{30} values like the site classification derived from the slope-derived V_s^{30} except for four sites where the slope-derived V_s^{30} values referred the sites as a Site class E instead of D1. The V_s^{30} values based on the SPT-N values at Gambila (KPK) and Sehwan (Sind) classify the sites as Site Class D3 and D1 whereas based on the slope-derived V_s^{30} values, these sites are classified as a Site Class D2 and D1. The Site class based on measured and slope derived V_s^{30} values in Punjab province shows variation within the same Site class i.e., Site class D. Most of the sites are classified as Site class D3 whereas slope-derived V_s^{30} map classifies most of them as Site class D1. The measured Site Class at Barnala site in AJK is matching well with the slope-derived Site class. Different measured site class locations in Peshawar show good agreement with the slope-derived V_s^{30} values.

The site classification based on SPT-N values varies from D1, D2, D3 and E whereas the Site Class according to slope-derived V_s^{30} values are D1 and D2. The Site Class E does not match with the slope-derived V_s^{30} value. The slope-derived V_s^{30} value classify the site in Bannu, BJC as a Site Class D2 whereas based on the SPT-N values, the site is classified as a Site Class C1, while the geological unit shows the same site class as of derived from the topographical slope V_s^{30}. Site classification based on SPT-N values for ten sites in zone A, B and C in ICT shows good matching with the Site class derived from slope-derived V_s^{30} values. The Site class for various sites based on the SPT-N values within the three zones (I, II and III) in Faisalabad city in Punjab province is mostly D2 and D3 whereas the slope-derived Site class is mostly D1 for all sites. The Site class for various sites within the five zones (1, 2, 3, 4 and 5) in Lahore city in Punjab province based on the SPT-N values is mostly D2 whereas the slope-derived Site class is mostly D1 for all sites. The shear wave velocity of about forty-nine (49) sites estimated at various locations in NA, AJK, and some parts of KPK based on the P-waves velocity values in which most of the sites, i.e., twenty-five (25) sites are matched well with the Site class derived from the topographic slope method that is Site class D (D2, D3), C (C1, C2, and C3) and B.

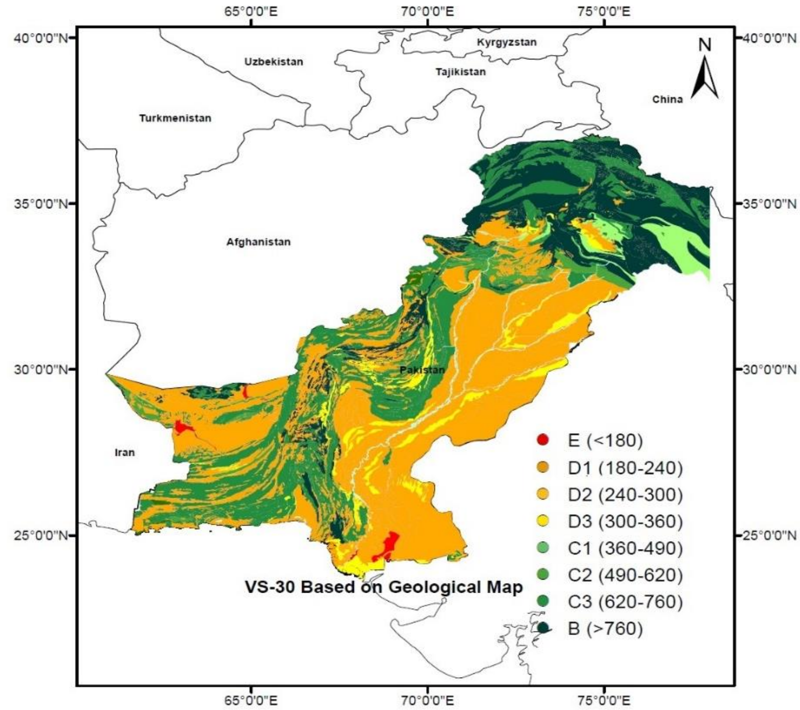
For five sites the estimated shear wave velocity gives Site class B but according to topographic slope method these sites are classified as Site class D (D3) and C (C1, C2, and C3). For four sites the estimated shear wave velocity gives Site class C3 but according to topographic slope method these sites are classified as Site class D1, C1, and B. For six sites the estimated shear wave velocity gives Site class C2 but according to topographic slope method these sites are classified as Site class D1, C1, and B. For the remaining eight sites the estimated shear wave velocity gives Site class C1 but according to the topographic slope method these sites are classified as Site class D1, C (C2, and C3) and B. Even though there is a difference in Site class for various sites in each province of Pakistan, the Wald et al., (2007) technique gives a good idea about the overall site classification.

Furthermore, the case of Islamabad and surrounding areas, where the slope-derived V_s^{30} map is matching reasonably well with the predicted V_s^{30} map based on the remote-sensing data (Yong et al., 2008). CESNED newsletter in 2007 published a report about the ―Coastal area of Sind susceptible to soil liquefaction and its mitigation. Based on the collected field data and observed satellite images, the coastal areas of Sind are susceptible to soil liquefaction. V_s^{30} values derived from the topographic slope method characterize the coastal area of Sind as a Site Class E and D1, which verifies the CESNED newsletter 2007 report. Most of the V_s^{30} values at various locations all over Pakistan show favorable agreement with the values derived from the proxy-based model. About 43% of the Site class at various locations matches with the Site class derived from the topographic slope method.

About 41% of the Site class at various locations varies within the same Site class and its subclasses. For example, in KPK where the Site class is type D3, but the slope-derived Site class is type D1, showing that the variation in the site classification remains in the same Site class. Most of the sites in the Punjab province are found to be in this category. About 15 % of the site class at various locations does not match with the Site class derived from the slope derived V_s^{30} map but if we match the geological based site class with the topographical slope derived class, maximum site classes matched. For example, in KPK where the Site Class is type D2, the slope-derived Site Class is type C1 but based on geologic units in area most of the site class lies within the range of topographical slope derived site class. Wald et al., (2007) proxy-based relation also works well in the case of Islamabad and surrounding areas where the site condition map, derived from the proxy-based model, is reasonably matching with the map obtained from the remote-sensing data (Yong et al., 2008).

There are some sites with steep slope but low V_s^{30} values and some sites with low slope but high V_s^{30} values. The sites which have steep slope but low V_s^{30} values and fail to occupy a place inside the specified predicting boxes are mostly located in the mountainous region within the small sedimentary basin missed by the larger resolution of DEM. Most of these sites are in KPK province and AJK whereas the sites which have low slope but high V_s^{30} values and fail to occupy a place inside the specified predicting boxes are mostly located either on a flat surface or on the rock outcrops within sedimentary basins. Most of these sites are in the Punjab province. As the site classification map based on V_s^{30} plays a key role in the accurate representation of the spatial distribution of ground motions in various seismic analyses such as seismic hazard analysis, and site response analysis.

Therefore, in the absence of measured V_s^{30} values for an area, the proxy-based model can be used to derive V_s^{30} values to be used in these analyses. The above-mentioned proxy-based model can be adapted to any region/area (modified active tectonic) as it extends a cost effective and efficient way to map V_s^{30} values.



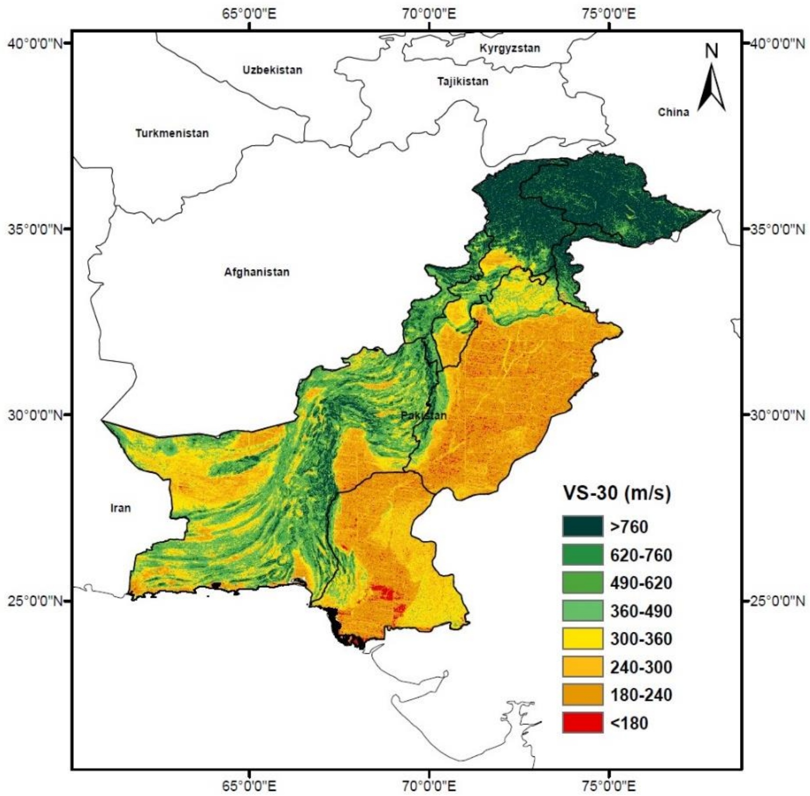


Fig 4-6 Comparison between Geology based V_s^{30} Map (Top) and Slope-Derived V_s^{30} Map (Bottom) of Pakistan

Chapter 5

Conclusions and Recommendations

To incorporate the effect of site-condition into seismic hazard assessment, site-condition map for Pakistan has been developed using the correlation between topographical slope and V_s^{30} measurements in active tectonic regions by employing Wald (2007) ‘s technique.

Following are some of the important conclusions of the current study

- Site-Classification map of Pakistan developed in the current study can be used as a first-order study in the absence of proper geotechnical and geological data.

- This first-order site-condition map of Pakistan will serve is a fundamental input into the decision-making process for earthquake loss mitigation.

- In this study, based on the borehole SPT data of sites, geology of the areas and slope derived derived V_s^{30} values for Pakistan. Islamabad predominately can be classified as seismic site class C, D and CD, which is from stiff soil to soft-rocky conditions. From the proposed maps based on the site class, earthquake resilient structures can be designed by structural engineers.

- The coastal areas of Sind; Liaqatpur, Bhawalnagar, Muzzafargarh, Layyah and Minchanabad tehsils in southern Punjab. Attock tehsil in northern Punjab. Malikwal, Waziarabad, Bhalwal and Sargodha tehsils in eastern Punjab, Darya Khan tehsil in western Punjab are susceptible to soil liquefaction as Site Class in these areas are mostly D1 (180-240) and have ability to liquify during earthquake occurrence.

- A weak link of the measured V_s^{30} with the topographical slope was present in Manshera, strongly controlled by the underlying geology.

Based on above conclusions following points can be recommended for future studies:

- This proxy-based V_s^{30} map can be used in the designing earthquake resilient structures in the absence of proper geotechnical data.
- A more accurate and complete picture of seismic hazard of Pakistan can be finally obtained by combining the PSHA maps with this first-order site-condition map.
- The derived V_s^{30}- site classification can be used to develop strategies for hazard management.
- The slope derived V_s^{30} map can be introduced in Updating and Implementation of the building code of Pakistan.
- Liquefaction and lateral spreading ground failure is possible in the areas of site class-D1, and site class-E, therefore site-specific investigations should be conducted in those areas.

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Appendix-A

Table A-1: Comparison of measured V_s^{30} observations with the slope derived V_s^{30} values and Geological Units

SR. NO	N	E	N-Value	Measured V_s^{30}	Slope Derived V_s^{30}	Geological Soil Character
1	33.76	73.22	50	453 (C1)	360-490	Tmm
2	33.68	72.80	12	358 (D3)	300-360	Q
3	33.52	73.18	48	445 (C1)	360-490	Tmc
4	33.99	71.44	58	480 (C1)	300-360	Q
5	32.75	72.70	58	441 (C1)	360-490	Tmr
6	33.62	73.17	12	343 (D3)	300-360	Tmm
7	33.62	73.18	6	301 (D3)	300-360	Tmm
8	33.57	73.20	14	367 (C1)	300-360	Tmd
9	33.68	72.83	14	367	360-490	Q
10	33.70	73	13	348	300-360	Q
11	33.84	72.64	8	318	240-300	Q
12	33.75	72.77	17	355	300-360	Q
13	33.64	72.95	16	354	300-360	Q
14	33.74	72.72	9	284	240-300	Q
15	33.68	72.83	25	427	360-490	Q
16	33.69	73.18	11	284	180-240	Tmm
17	33.63	72.92	12	319	300-360	Q
18	33.63	72.92	20	391	300-360	Q
19	33.68	73.00	9	284	240-300	Q
20	33.68	73.00	10	296	240-300	Q
21	33.68	73.01	9	331	240-300	Q
22	33.68	73.01	11	308	240-300	Q
23	33.70	72.98	15	348	300-360	Q
24	33.70	72.98	16	358	300-360	Q
25	33.73	73.06	33	478	360-490	Q
26	33.73	73.06	33	478	360-490	Q
27	33.63	72.92	13	329	300-360	Q
28	33.63	72.92	14	339	300-360	Q
29	33.63	72.90	16	358	300-360	Q
30	33.63	72.92	14	339	300-360	Q
31	33.63	72.92	12	319	300-360	Q
32	33.63	72.92	12	319	300-360	Q
33	33.63	72.92	13	329	300-360	Q
34	33.63	72.92	14	339	300-360	Q
35	33.68	72.99	11	308	240-300	Q
36	33.68	72.99	13	329	240-300	Q
37	33.63	72.92	15	348	300-360	Q
38	33.63	72.92	14	339	300-360	Q
39	33.63	72.92	15	348	300-360	Q
40	33.71	72.98	14	339	300-360	Q
41	33.71	72.98	11	308	300-360	Q
42	33.72	73.06	10	296	300-360	Q
43	33.67	73.07	10	296	240-300	Q
44	33.67	73.07	9	284	240-300	Q
45	33.70	72.97	18	375	300-360	Q
46	33.70	72.97	16	358	300-360	Q
47	33.64	72.95	13	329	300-360	Q
48	33.70	72.97	14	339	300-360	Q
49	33.70	72.97	16	358	300-360	Q
50	33.70	72.97	11	308	300-360	Q
51	33.70	72.97	12	319	300-360	Q

52	33.66	73.07	11	308	240-300	Q
53	33.66	73.07	10	296	240-300	Q
54	33.70	72.97	15	348	300-360	Q
55	33.70	72.97	14	339	300-360	Q
56	33.64	72.95	14	339	300-360	Q
57	33.70	72.97	20	391	300-360	Q
58	33.70	72.97	14	339	300-360	Q
59	33.66	72.96	8	271	180-240	Q
60	33.66	72.96	7	257	180-240	Q
61	33.72	73.09	15	348	300-360	Q
62	33.72	73.09	13	329	360-490	Q
63	33.70	72.97	19	383	300-360	Q
64	33.70	72.97	16	358	300-360	Q
65	33.70	72.94	20	391	300-360	Q
66	33.70	72.97	21	399	300-360	Q
67	33.70	72.98	16	358	300-360	Q
68	33.70	72.98	15	348	300-360	Q
69	33.72	73.05	17	366	300-360	Q
70	33.70	72.98	18	375	300-360	Q
71	33.70	72.98	15	348	300-360	Q
72	33.67	73.04	10	296	180-240	Q
73	33.67	73.04	9	284	180-240	Q
74	33.67	73.04	10	296	180-240	Q
75	33.67	73.04	8	271	180-240	Q
76	33.65	72.95	15	348	300-360	Q
77	33.63	72.92	15	348	300-360	Q
78	33.63	72.92	16	358	300-360	Q
79	33.70	72.98	15	348	300-360	Q
80	33.70	72.98	14	339	300-360	Q
81	33.70	72.97	14	339	300-360	Q
82	33.70	72.97	16	358	300-360	Q
83	33.70	73.06	14	339	300-360	Q
84	33.70	73.05	16	358	300-360	Q
85	33.70	73.05	15	348	300-360	Q
86	33.63	72.92	14	339	300-360	Q
87	33.63	72.92	15	348	300-360	Q
88	33.72	73.06	17	366	300-360	Q
89	33.72	73.06	16	358	300-360	Q
90	33.70	72.97	12	319	300-360	Q
91	33.70	72.97	13	329	300-360	Q
92	33.63	72.93	19	383	300-360	Q
93	33.63	72.93	16	358	300-360	Q
94	33.63	72.93	15	348	300-360	Q
95	33.63	72.93	16	358	300-360	Q
96	33.66	73.04	11	308	240-300	Q
97	33.66	73.04	12	319	240-300	Q
98	33.70	72.97	23	413	360-490	Q
99	33.60	72.93	11	308	240-300	Q
100	33.60	72.93	10	296	240-300	Q
101	33.70	72.98	10	296	300-360	Q
102	33.70	72.98	11	308	300-360	Q
103	33.70	72.97	17	366	360-490	Q
104	33.70	72.97	18	375	360-490	Q
105	33.68	72.84	34	483	360-490	Q
106	33.68	72.84	32	472	360-490	Q
107	33.67	73.07	12	319	240-300	Q
108	33.67	73.07	11	308	240-300	Q
109	33.69	73.06	14	339	300-360	Q
110	33.69	73.06	15	348	300-360	Q
111	33.70	72.98	16	358	300-360	Q
112	33.70	72.98	14	339	300-360	Q
113	33.70	72.98	13	329	300-360	Q
114	33.70	72.98	16	358	300-360	Q
115	33.70	72.98	15	348	300-360	Q
116	33.68	73.07	11	308	240-300	Q

117	33.68	73.07	12	319	240-300	Q
118	33.68	73.07	10	296	240-300	Q
119	33.71	73.05	16	358	300-360	Q
120	33.71	73.05	15	348	300-360	Q
121	33.73	73.07	13	329	300-360	Q
122	33.73	73.07	12	319	300-360	Q
123	33.69	72.83	16	358	300-360	Q
124	33.69	72.83	17	366	300-360	Q
125	33.68	72.83	18	375	300-360	Q
126	33.68	72.83	16	358	300-360	Q
127	33.70	72.97	19	383	300-360	Q
128	33.70	72.97	18	375	300-360	Q
129	33.70	72.97	17	366	300-360	Q
130	33.70	72.97	16	358	300-360	Q
131	33.69	72.99	15	348	300-360	Q
132	33.69	72.99	14	339	300-360	Q
133	33.66	72.97	10	296	180-240	Q
134	33.66	72.97	9	284	180-240	Q
135	33.70	72.98	12	319	300-360	Q
136	33.70	72.98	13	329	300-360	Q
137	33.67	73.08	10	296	240-300	Q
138	33.67	73.08	9	284	240-300	Q
139	33.67	73.08	9	284	240-300	Q
140	33.66	72.97	11	308	240-300	Q
141	33.66	72.97	10	296	240-300	Q
142	33.68	73.00	18	375	360-490	Q
143	33.68	73.00	19	383	360-490	Q
144	33.68	73.00	18	375	360-490	Q
145	33.68	73.00	18	375	360-490	Q
146	33.68	73.00	19	383	360-490	Q
147	33.70	72.99	16	358	300-360	Q
148	33.70	72.99	15	348	300-360	Q
149	33.73	73.08	32	472	360-490	Q
150	33.73	73.08	33	478	360-490	Q
151	33.67	73.00	28	447	360-490	Q
152	33.67	73.00	29	454	360-490	Q
153	33.70	72.97	11	308	300-360	Q
154	33.69	72.97	10	296	240-300	Q
155	33.68	73.03	9	284	240-300	Q
156	33.68	73.03	10	296	240-300	Q
157	33.70	72.99	12	319	300-360	Q
158	33.70	72.99	15	348	300-360	Q
159	33.66	72.96	6	241	180-240	Q
160	33.66	72.96	6	241	180-240	Q
161	33.71	73.04	13	329	300-360	Q
162	33.71	73.04	11	308	300-360	Q
163	33.66	72.88	18	375	300-360	Q
164	33.66	72.88	22	406	300-360	Q
165	33.70	72.97	13	329	300-360	Q
166	33.70	72.97	12	319	300-360	Q
167	33.70	72.97	11	308	300-360	Q
168	33.66	73.04	10	296	240-300	Q
169	33.66	73.04	10	296	240-300	Q
170	33.66	73.04	9	284	240-300	Q
171	33.66	73.04	10	296	240-300	Q
172	33.66	72.85	17	366	300-360	Q
173	33.66	72.86	16	358	300-360	Q
174	33.71	73.04	11	308	300-360	Q
175	33.71	73.04	10	296	300-360	Q
176	33.67	73.08	10	296	240-300	Q
177	33.67	73.08	10	296	240-300	Q
178	33.67	73.08	8	271	240-300	Q
179	33.69	72.98	12	319	240-300	Q
180	33.69	72.98	10	296	240-300	Q
181	33.65	72.85	35	489	360-490	Q

182	33.65	72.85	34	483	360-490	Q
183	33.70	72.97	19	383	300-360	Q
184	33.70	72.97	18	375	300-360	Q
185	33.69	72.83	16	358	300-360	Q
186	33.69	72.83	18	375	300-360	Q
187	33.70	72.98	11	308	300-360	Q
188	33.70	72.98	12	319	300-360	Q
189	33.70	72.98	13	329	300-360	Q
190	33.70	72.98	12	319	300-360	Q
191	33.66	73.08	12	319	240-300	Q
192	33.66	73.08	10	296	240-300	Q
193	33.71	72.95	25	427	360-490	Q
194	33.71	72.95	28	447	360-490	Q
195	33.66	72.96	8	271	180-240	Q
196	33.66	72.96	7	257	180-240	Q
197	33.70	72.97	12	319	300-360	Q
198	33.70	72.97	12	319	300-360	Q
199	33.65	72.95	10	296	240-300	Q
200	33.65	72.95	10	296	240-300	Q
201	33.70	72.97	15	348	300-360	Q
202	33.70	72.97	16	358	300-360	Q
203	33.73	73.07	38	505	360-490	Q
204	33.73	73.07	36	495	360-490	Q
205	33.69	72.83	20	391	300-360	Q
206	33.69	72.83	18	375	300-360	Q
207	33.75	72.77	15	348	300-360	Q
208	33.82	72.72	16	358	240-300	Q
209	25.60	68.51	19	294	180-240	Qfx
210	25.55	68.48	6	188	<180	Qfx
211	25.50	68.42	10	229	180-240	Qfx
212	25.50	68.34	11	238	180-240	Qfx
213	26.89	68.26	11	238	180-240	Qmx
214	26.86	68.25	10	229	180-240	Qmx
215	26.79	68.25	15	269	180-240	Qcm
216	26.71	68.24	12	246	180-240	Qcm
217	26.68	68.24	11	238	180-240	Qmx
218	26.67	68.24	10	229	180-240	Qmx
219	26.62	68.24	11	238	180-240	Qmx
220	26.59	68.24	9	220	180-240	Qmx
221	26.67	68.24	9	220	180-240	Qmx
222	26.53	68.26	8	210	180-240	Qcm
223	26.48	68.28	10	229	180-240	Qmx
224	26.45	68.29	11	238	180-240	Qmx
225	26.36	68.31	11	238	180-240	Qfx
226	26.22	68.34	12	246	180-240	Qmx
227	26.17	68.35	12	246	180-240	Qfx
228	26.12	68.35	8	210	180-240	Qfx
229	26.09	68.36	6	188	<180	Qfx
230	26.03	68.38	12	246	180-240	Qfx
231	25.96	68.41	10	229	180-240	Qfx
232	25.85	68.49	12	246	180-240	Qmx
233	25.78	68.52	11	238	180-240	Qmx
234	25.75	68.53	10	229	180-240	Qfx
235	25.69	68.53	10	229	180-240	Qfx
236	25.65	68.53	12	246	180-240	Q
237	25.51	68.32	12	246	180-240	Q
238	25.49	68.27	12	246	180-240	Teg
239	25.45	68.25	13	254	180-240	Tr
240	25.38	68.24	12	246	240-300	Tr
241	24.34	68.90	Direct V_s^{30}	180-240 (D1)	180-240	Qdx
242	24.63	69.24	-do-	180-240 (D1)	360-490	Qmx
243	24.68	69.21	-do-	180-240 (D1)	300-360	Qmx
244	24.68	69.22	-do-	180-240 (D1)	300-360	Qmx
245	24.82	69.33	-do-	180 (E)	300-360	Qmx
246	24.83	69.39	-do-	180-240 (D1)	360-490	Qmx

247	24.87	69.33	-do-	180-240 (D1)	360-490	Qmx
248	24.93	69.43	-do-	180-240 (D1)	360-490	Qmx
249	25.00	69.29	-do-	180-240 (D1)	300-360	Qmx
250	25.05	68.86	-do-	180-240 (D1)	>760	Qmx
251	25.08	69.64	-do-	180-240 (D1)	360-490	Qmx
252	25.13	68.88	-do-	180-240 (D1)	360-490	Qmx
253	25.15	69.19	-do-	180-240 (D1)	240-300	Qmx
254	25.17	69.11	-do-	180-240 (D1)	300-360	Qmx
255	25.22	68.73	-do-	180-240 (D1)	360-490	Qfx
256	25.29	68.88	-do-	180-240 (D1)	360-490	Qmx
257	25.29	69.08	-do-	180-240 (D1)	300-360	Qmx
258	25.30	69.09	-do-	180-240 (D1)	180-240	Qmx
259	25.30	69.54	-do-	180 (E)	240-300	Qmx
260	25.46	69.40	-do-	180 (E)	180-240	Qmx
261	25.49	68.85	-do-	180-240 (D1)	180-240	Qmx
262	25.52	69.19	-do-	180-240 (D1)	<180	Qmx
263	25.71	68.72	-do-	180-240 (D1)	180-240	Qmx
264	25.81	68.74	-do-	180-240 (D1)	180-240	Qmx
265	25.90	68.59	-do-	180-240 (D1)	180-240	Qmx
266	26.43	67.85	5 to 22	180-240 (D1)	180-240	Qmx
267	27.20	68.55	-do-	180 (E)	<180	Qmx
268	27.32	68.65	-do-	180-240 (D1)	240-300	Qmx
269	27.60	69.54	-do-	240-300 (D2)	180-240	Qmx
270	27.86	69.40	-do-	180-240 (D1)	180-240	Qmx
271	27.93	69.33	-do-	180-240 (D1)	<180	Qmx
272	27.95	69.69	Overall variation 4->50	180-240 (D1)	180-240	Qmx
273	29.53	71.64	13	180-240 (D1)	180-240	Qfx
274	30.08	66.99	Direct V_s^{30}	360-490 (C)	<180	Q
275	30.09	66.93	Direct V_s^{30}	360-490 (C)	<180	Q
276	30.09	66.99	Direct V_s^{30}	360-490 (C)	<180	Q
277	30.10	66.94	Direct V_s^{30}	360-490 (C)	<180	Q
278	30.16	66.96	Direct V_s^{30}	240-300 (D)	180-240	Q
279	30.17	66.97	Direct V_s^{30}	300-360 (D)	180-240	Q
280	30.17	67.00	Direct V_s^{30}	300-360 (D)	180-240	Q
281	30.17	67.02	Direct V_s^{30}	620-760 (B)	<180	Q
282	30.18	66.96	Direct V_s^{30}	360-490 (C)	<180	Q
283	30.19	71.47	13	240-300 (D2)	240-300	Q
284	30.22	66.95	Direct V_s^{30}	360-490 (C)	300-360	Q
285	30.22	67.00	Direct V_s^{30}	360-490 (C)	180-240	Q
286	30.22	67.04	Direct V_s^{30}	360-490 (C)	<180	Q
287	30.23	66.94	Direct V_s^{30}	360-490 (C)	180-240	Q
288	30.29	73.07	15	180-240 (D1)	180-240	Q
289	30.33	73.38	11	180-240 (D1)	180-240	Q
290	30.64	72.30	12	180-240 (D1)	180-240	Q
291	30.67	73.10	11	180-240 (D1)	180-240	Q
292	30.96	73.97	11	240-300 (D2)	240-300	Q
293	31.24	74.21	4 to 44	180-240 (D1)	180-240	Q
294	31.31	72.33	13	180-240 (D1)	180-240	Q
295	31.36	73.11	15-20	180-240 (D1)	180-240	Q
296	31.37	72.94	22-25	180-240 (D1)	240-300	Q
297	31.37	73.02	18-20	180-240 (D1)	180-240	Qc
298	31.38	73.05	18-20	180-240 (D1)	180-240	Qc
299	31.40	74.14	5 to 71	300-360 (D3)	240-300	Qc
300	31.40	74.26	4 to 44	180-240 (D1)	240-300	Qc
301	31.41	73.07	12	180-240 (D1)	240-300	Qc
302	31.42	73.08	18-20	180-240 (D1)	180-240	Qc
303	31.43	74.26	4 to 44	180-240 (D1)	180-240	Qc
304	31.43	74.35	3 to 40	180-240 (D1)	180-240	Qc
305	31.44	74.22	4 to 44	180-240 (D1)	300-360	Qc
306	31.46	72.96	22-25	180-240 (D1)	180-240	Qc
307	31.46	74.10	5 to 71	180-240 (D1)	240-300	Qc
308	31.46	74.29	1 to 51	180-240 (D1)	240-300	Qc
309	31.47	74.39	3 to 40	180-240 (D1)	300-360	Qc
310	31.47	74.51	3 to 40	180-240 (D1)	240-300	Qc

311	31.48	74.32	1 to 51	180-240 (D1)	240-300	Qc
312	31.48	74.38	3 to 40	180-240 (D1)	300-360	Qc
313	31.49	72.98	22-25	180-240 (D1)	300-360	Qc
314	31.50	73.17	18-20	180-240 (D1)	240-300	Qc
315	31.50	74.15	9.78	180-240 (D1)	240-300	Qc
316	31.50	74.34	1 to 51	180-240 (D1)	360-490	Qc
317	31.51	74.28	1 to 51	180-240 (D1)	240-300	Qc
318	31.52	73.02	18-20	180-240 (D1)	300-360	Qc
319	31.52	74.34	1 to 51	180-240 (D1)	490-620	Qc
320	31.53	74.46	3 to 40	180-240 (D1)	490-620	Qc
321	31.54	74.38	3 to 37	180-240 (D1)	360-490	Qc
322	31.57	74.31	3 to 37	300-360 (D3)	490-620	Qc
323	31.58	74.31	3 to 37	300-360 (D3)	180-240	Qc
324	31.58	74.37	3 to 37	180-240 (D1)	180-240	Qc
325	31.59	74.22	5 to 71	180-240 (D1)	180-240	Qc
326	31.59	74.24	4 to 44	180-240 (D1)	180-240	Qc
327	31.59	74.33	3 to 37	180-240 (D1)	180-240	Qc
328	31.62	74.27	5 to 71	180-240 (D1)	180-240	Qc
329	31.64	74.36	5 to 71	180-240 (D1)	180-240	Qc
330	31.71	73.98	9.78	180-240 (D1)	180-240	Qc
331	32.09	74.87	9.49	180-240 (D1)	180-240	Qc
332	32.15	74.18	9.78	180-240 (D1)	180-240	Qc
333	32.34	73.67	-do-	180-240 (D1)	180-240	Qc
334	32.34	73.70	-do-	180-240 (D1)	<180	Qc
335	32.49	74.53	9.49	180-240 (D1)	180-240	Qc
336	32.68	70.77	8 to 50	240-300 (D2)	180-240	Qc
337	32.91	74.11	2 to 27	300-360 (D3)	180-240	Qpd
338	32.99	70.62	3 to 42	240-300 (D2)	180-240	Q
339	33.10	74.11	-do-	620-760 (C3)	240-300	Tns
340	33.19	73.91	-do-	490-620 (C2)	180-240	Qp
341	33.22	71.50	Direct V_s^{30}	360-490 (C1)	180-240	Tmn
342	33.23	73.78	-do-	300-360 (D3)	180-240	Qp
343	33.31	73.85	-do-	360-490 (C1)	180-240	Tns
344	33.31	73.95	-do-	490-620 (C2)	180-240	Tns
345	33.32	73.68	-do-	360-490 (C1)	180-240	Tns
346	33.38	73.78	-do-	490-620 (C2)	180-240	Tns
347	33.52	73.76	-do-	490-620 (C2)	<180	Q
348	33.62	72.99	21-26	300-360 (D3)	180-240	Tns
349	33.64	72.94	7 to 12	240-300 (D2)	180-240	Q
350	33.64	73.82	-do-	490-620 (C2)	<180	Q
351	33.69	72.94	7 to 12	240-300 (D2)	240-300	Tmm
352	33.69	72.98	7 to 12	240-300 (D2)	180-240	Q
353	33.70	73.09	Direct V_s^{30}	300-360 (D3)	180-240	Q
354	33.70	73.11	21-26	300-360 (D3)	180-240	Q
355	33.70	73.95	-do-	760 (B)	180-240	Tmm
356	33.71	73.16	21-26	300-360 (D3)	240-300	Tmm
357	33.73	73.04	23-78	490-620 (C2)	>760	Q
358	33.75	73.18	23-78	360-490 (C1)	300-360	Tmm
359	33.76	73.12	23-78	490-620 (C2)	>760	Q
360	33.77	73.32	-do-	490-620 (C2)	620-760	Tmm
361	33.77	73.89	-do-	490-620 (C2)	490-620	Tmm
362	33.78	73.10	23-78	490-620 (C2)	490-620	Q
363	33.86	73.76	-do-	620-760 (C3)	>760	Tmm
364	33.86	73.83	-do-	620-760 (C3)	490-620	Tmm
365	33.92	73.77	-do-	760 (B)	620-760	Tmm
366	33.96	71.46	-do-	300-360 (D3)	360-490	Q
367	33.97	73.81	P to S Waves	760 (B)	490-620	Tmm
368	33.99	71.42	-do-	360-490 (C1)	620-760	Q
369	33.99	71.57	18	240-300 (D2)	490-620	Q
370	34.00	71.57	16	240-300 (D2)	490-620	Q
371	34.00	73.64	-do-	760 (B)	360-490	Tmm
372	34.03	71.49	3	240-300 (D2)	360-490	Q
373	34.03	72.53	-do-	180-240 (D1)	360-490	Q
374	34.04	71.65	4	180-240 (D1)	300-360	Q
375	34.04	73.58	-do-	360-490 (C1)	360-490	Tmm

376	34.05	71.46	18	240-300 (D2)	>760	Q
377	34.06	71.54	9	180-240 (D1)	490-620	Q
378	34.07	73.53	-do-	760 (B)	360-490	Tmm
379	34.08	73.28	-do-	620-760 (C3)	240-300	Pem
380	34.10	72.00	Direct V_s^{30}	180-240 (D1)	360-490	Q
381	34.11	73.72	-do-	760 (B)	490-620	Tmm
382	34.17	73.74	-do-	360-490 (C1)	490-620	Tmm
383	34.22	73.61	-do-	760 (B)	360-490	Tmm
384	34.23	73.62	-do-	490-620 (C2)	300-360	Tmm
385	34.32	71.58	-do-	240-300 (D2)	300-360	Q
386	34.33	73.20	Direct V_s^{30}	360-490 (C1)	620-760	Q
387	34.36	73.26	-do-	490-620 (C2)	490-620	Q
388	34.39	72.51	-do-	490-620 (C2)	490-620	Q
389	34.39	73.31	-do-	360-490 (C1)	180-240	Q
390	34.45	73.78	-do-	760 (B)	360-490	Pes
391	34.50	71.95	-do-	360-490 (C1)	>760	Q
392	34.55	73.36	-do-	760 (B)	490-620	Q
393	34.84	73.03	-do-	490-620 (C2)	180-240	eg
394	34.88	72.83	-do-	760 (B)	>760	pcb
395	34.92	74.30	-do-	760 (B)	490-620	eg
396	35.11	73.01	-do-	760 (B)	360-490	Jk
397	35.27	73.22	-do-	760 (B)	180-240	Jk
398	35.28	75.63	-do-	620-760 (C3)	>760	Tkm
399	35.29	75.65	-do-	360-490 (C1)	>760	Tkm
400	35.42	74.10	-do-	620-760 (C3)	>760	Kjc
401	35.69	74.63	-do-	360-490 (C1)	620-760	Tkm
402	35.86	71.79	-do-	360-490 (C1)	620-760	Kkg
403	35.89	74.47	-do-	760 (B)	620-760	Mpzs
404	35.92	74.32	-do-	760 (B)	>760	Tkk
405	36.32	74.67	-do-	760 (B)	>760	Peb
406	33.63	72.94	-do-	260	240-300	P
407	33.74	73.11	-do-	267	360-490	P
408	33.69	73.04	-do-	283	240-300	B
409	33.78	73.24	-do-	429	360-490	M
410	33.74	73.20	-do-	417	300-360	M
411	33.64	73.16	-do-	299	240-300	P
412	33.74	73.06	-do-	421	620-760	L
413	33.52	73.16	-do-	260	300-360	P
414	33.55	73.09	-do-	260	360-490	C
415	33.53	73.18	-do-	253	360-490	X
416	33.55	73.24	-do-	332	360-490	P
417	33.70	72.97	-do-	422	300-360	M
418	33.73	73.04	-do-	272	490-620	A
419	33.72	73.10	-do-	327	360-490	T
420	33.68	72.99	-do-	242	240-300	B
421	33.68	73.00	-do-	244	240-300	P
422	33.64	72.92	-do-	274	300-360	B
423	33.73	73.08	-do-	270	360-490	T
424	33.71	73.04	-do-	271	300-360	A
425	33.72	73.03	-do-	271	360-490	A
426	33.71	73.03	-do-	248	240-300	A
427	33.73	73.04	-do-	404	490-620	L
428	33.68	73.08	-do-	343	300-360	P
429	33.67	72.99	-do-	318	300-360	B
430	33.65	72.96	-do-	436	240-300	M
431	33.65	72.96	-do-	265	240-300	B
432	33.63	72.92	-do-	244	300-360	B
433	33.63	72.92	-do-	257	300-360	B
434	33.64	72.92	-do-	329	300-360	B
435	33.63	72.92	-do-	266	300-360	B
436	33.70	73.08	-do-	370	300-360	M
437	33.71	73.05	-do-	233	300-360	B
438	33.69	73.03	-do-	285	240-300	B
439	33.68	73.03	-do-	267	240-300	B
440	33.69	73.03	-do-	247	240-300	P

441	33.67	73.16	-do-	214	180-240	B
442	33.60	73.15	-do-	327	360-490	G
443	33.56	73.11	-do-	249	360-490	C
444	33.66	73.01	-do-	270	300-360	B
445	33.65	72.99	-do-	417	300-360	M
446	33.67	73.05	-do-	351	240-300	P
447	33.66	73.04	-do-	267	240-300	B
448	33.64	73.03	-do-	356	240-300	P
449	33.66	73.05	-do-	265	180-240	B
450	33.57	73.23	-do-	411	300-360	S
451	33.73	73.15	-do-	276	360-490	T
452	33.72	73.23	-do-	399	300-360	S
453	33.66	73.10	-do-	372	240-300	P
454	33.58	73.28	-do-	384	360-490	H
455	33.56	73.18	-do-	412	240-300	F
456	33.69	73.27	-do-	372	300-360	P
457	33.75	73.14	-do-	270	360-490	T
458	33.69	73.12	-do-	419	240-300	M
459	33.69	73.12	-do-	316	240-300	P
460	33.74	73.07	-do-	338	490-620	P
461	33.67	72.84	-do-	318	240-300	P
462	33.68	72.91	-do-	397	360-490	P
463	33.78	73.17	-do-	298	360-490	P
464	33.69	73.08	-do-	266	300-360	C
465	33.55	73.20	-do-	255	240-300	B
466	33.54	73.12	-do-	250	240-300	P
467	33.71	72.98	-do-	397	300-360	A
468	33.73	73.04	-do-	421	490-620	B
469	33.71	73.02	-do-	413	300-360	A
470	33.69	72.97	-do-	467	240-300	L
471	33.74	73.06	-do-	338	620-760	L
472	33.67	73.21	-do-	214	240-300	P
473	33.63	73.13	-do-	417	180-240	S
474	33.60	72.98	-do-	250	300-360	P
475	33.60	73.06	-do-	259	240-300	P
476	33.63	72.81	-do-	401	300-360	L
477	33.55	72.87	-do-	403	300-360	B
478	33.55	72.96	-do-	240	240-300	B
479	33.51	73.35	-do-	408	240-300	X
480	33.57	73.29	-do-	419	360-490	H
481	33.57	73.31	-do-	383	300-360	H
482	33.51	73.29	-do-	400	360-490	P
483	33.58	73.33	-do-	414	240-300	P
484	33.53	73.06	-do-	249	360-490	C
485	33.57	73.01	-do-	247	180-240	P
486	33.58	72.83	-do-	340	300-360	B
487	33.61	72.89	-do-	414	300-360	P
488	33.60	72.85	-do-	388	300-360	P
489	33.58	72.88	-do-	235	300-360	P
490	33.52	73.00	-do-	374	300-360	M
491	34.43	73.36	-do-	339	490-620	P
492	34.53	73.35	-do-	237	>760	Peb
493	34.48	73.37	-do-	318	>760	Peb
494	34.40	73.37	-do-	307	620-760	P
495	34.53	73.35	-do-	276	>760	P
496	34.44	73.36	-do-	243	620-760	Peb
497	34.52	73.35	-do-	281	>760	Tmm
498	34.53	73.35	-do-	251	>760	Tmm
499	34.57	73.35	-do-	353	620-760	Tmm
500	34.54	73.35	-do-	173	>760	Peb
501	34.54	73.35	-do-	229	>760	Peb
502	34.46	73.35	-do-	214	360-490	Q
503	34.53	73.36	-do-	219	>760	P
504	34.56	73.34	-do-	223	>760	P
505	34.49	73.36	-do-	241	>760	P

506	34.45	73.35	-do-	298	360-490	Q
507	34.56	73.36	-do-	250	>760	Peb
508	34.56	73.35	-do-	206	490-620	Peb
509	34.53	73.36	-do-	183	>760	Pb
510	34.44	73.36	-do-	270	620-760	Pb
511	34.56	73.35	-do-	266	360-490	Q
512	34.49	73.36	-do-	385	>760	Q
513	28.93	70.95	-do-	D1	180-240	Q
514	30.03	73.24	-do-	D1	180-240	Q
515	30.07	71.18	-do-	D1	180-240	Q
516	30.97	70.94	-do-	D1	180-240	Q
517	30.16	73.57	-do-	D1	180-240	Q
518	33.77	72.36	-do-	D1	240-300	Q
519	32.55	73.21	-do-	D1	180-240	Q
520	32.44	74.12	-do-	D1	180-240	Q
521	32.28	72.90	-do-	D1	180-240	Q
522	32.07	72.69	-do-	D1	180-240	Q
523	31.79	71.11	-do-	E	<180	Q
524	33.86	72.41	-do-	294	240-300	Q