50th IGC

50th INDIAN GEOTECHNICAL CONFERENCE
17th – 19th DECEMBER 2015, Pune, Maharashtra, India
Venue: College of Engineering (Estd. 1854), Pune, India

ATTENUATION OF P AND S WAVES FOR CHAMBA REGION

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ABSTRACT

In order to minimize the structural damages during an earthquake, the proper estimation of ground motions is desired. Considering the present codal recommendations, these ground motions can be considered in earthquake resistant design in the form of average response acceleration coefficient. These level of ground shaking varies from site to site and can be divided into bedrock level ground motions and its alteration due to the presence of local soils. In order to determine bedrock level ground motion characteristics for the future earthquake, it is required to perform the seismic hazard analysis of the site under consideration. Depending upon the structural requirements, a seismic hazard analysis can be performed deterministically or probabilistically. Either methods of seismic hazard assessment requires a region specific attenuation relation. These attenuation relations are developed based on regional earthquake data and in absence of large recorded data, synthetic ground motions are also extensively used while developing such attenuation relations. For regions with low or moderate seismic activity or limited ground motion records, it is preferable to go for synthetic ground motion. Stochastic ground motion simulation models are used to develop acceleration time history at the site. Fourier acceleration amplitude spectrum is developed synthetically for a site for a known earthquake magnitude M occurring at an epicentral distance of R. Development of such Fourier acceleration amplitude spectrum requires numerous model parameters. One such crucial parameter is the quality factor. This frequency dependent quality factor varies from site to site depending on geological formation of the sites. Quality factor is defined as $Q(f)=Q_0f^n$ where Q_o is the value of Q at 1Hz frequency and n is a numerical constant. Low Q values for a particular site defines that the site is within an active seismic zone. Further, there are uncertainties in the determination of $Q(f)$ values. The Quality factor for a particular place can also vary due to the consideration of ground motion database within a certain range of earthquake magnitude. This quality factor is important while defining the diminution function, one of the model parameter that takes care of the effects of seismic wave propagation path attenuation. For a particular site there can be various source and different forms of seismic wave propagation path so accordingly there will be various diminution functions representing such possible variations. Another important model parameter is the upper crustal attenuation factor $P(f)$ which is defined by $e^{-\pi f k}$. k parameter is associated with the near surface attenuation of the seismic waves. Determination of κ parameters also involves lot of uncertainties in its definition. Hence, in order to determine the realistic ground motion characteristics for a particular region, values of above parameters should be known with accuracy. In the present, an attempt is made to determine the value of P and S wave Quality factors based on recorded ground motions at Chamba located in the north western Himalayan belt. 11 different earthquake events during 2009 to 2014 recorded at Chamba station are used to find out the quality factors $Q_P = 98f^{0.96}$

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and $Q_S = 173f^{0.87}$ for P and S wave respectively. Estimated values of Quality factors for frequency range (0.5 – 15 Hz) from the present work are found consistent with the existing literature for NW Himalayan belt. The obtained $^{Q_S}/_{Q_P}$ ratio is greater than 1 for all frequency range which is appropriate for this region. These frequency dependent attenuation characteristics of a medium for P and S waves are very important for ground motion prediction and seismic hazard assessment for Chamba region.

Keywords: Quality factor(Q), Attenuation of P wave and S wave, Coda normalization method.

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ABSTRACT: In the present work, the attenuation of P and S wave have been studied for Chamba area in NW Himalaya region using extended coda normalization method. A total of 11 earthquake events with magnitude range of 3.0 to 5.0 are considered. The frequency dependent study is done within a frequency range between 0.5 and 15.0 Hz. Based on the analyses, observed quality factors of $Q_P = 98f^{0.96}$ & $Q_S = 173f^{0.87}$ are found for P and S wave respectively, which indicates the seismic activity and heterogeneity of the region. Obtained values are well in accordance with the available literature for NW Himalayan region. The ratio ${Q_S}/{Q_P}$ is greater than 1 for the entire frequency range which is matching with the findings from other researchers for the region. These findings will be useful in understanding the P and S wave attenuation for Chamba region. Based on attenuation characteristics, assessment of damage pattern for future earthquakes can be attempted in further works.

INTRODUCTION

Attenuation characteristics is an important factor when the effects of seismic wave path propagation is considered. To learn about the earth's internal structure and for prediction of strong earthquake ground motion, attenuation characteristics of crust are required. Attenuation characteristics of medium are represented as the inverse of quality factor (Q) which indicates the wave transmission quality of the bed rock [1]. A region with high Q value generally assumed as a stable region whereas low Q value represents seismically active region [2]. Based on wave transmission quality of a medium, attenuation properties of medium are defined which governs the decay in the amplitudes of seismic waves between the source and the site. Attenuation of seismic waves occurs due to geometrical spreading, conversion of seismic energy in the form of heat i.e. intrinsic attenuation and redistribution of energy due to presence of heterogeneities in wave propagation medium i.e. scattering attenuation [3]. The attenuation of seismic wave shows direct relation with total energy of harmonic waves and is given by $Q^{-1} = -{\Delta E}/{2\pi E}$ where ΔE is the energy lost per cycle and E is total energy of harmonic wave [4]. As the total energy of P and S wave are different from each other hence researchers have found that the attenuation of P wave (${Q_P}^{-1}$) is different from attenuation of S wave (${Q_S}^{-1}$) [5]. Further, these studies have revealed the frequency dependent characteristics of both ${Q_P}^{-1}$ and ${Q_S}^{-1}$ which gives the attenuation ratio ${{Q_P}^{-1}}/{{Q_S}^{-1}} \cong {V_P}/{V_S}$ (V_P refers to P wave velocity and V_S refers to S wave velocity) [6]. This relation was observed to be valid within frequency range 1.0 Hz to 30.0 Hz. However, this ratio decreases with the decrease in frequency below 1.0 Hz [7].

Attenuation of direct P and S waves can be estimated using coda normalization method in which the spectral amplitudes of P and S waves are normalized by the RMS (Root Mean Square) amplitude of coda waves. The coda wave arrives after the arrival of all direct waves as a result of reflection and refraction from various surfaces. For this reason, the coda signature appears at the tail of a seismogram records. The spectral amplitude of direct waves strongly depend on hypocentral distance and wave propagation path characteristics whereas for coda waves this dependence on hypocentral distance diminishes [8]. Therefore, decay in the amplitude of coda waves shows the attenuation characteristics of the whole region instead of a particular path. These coda waves are generated due to backscattering of P and S waves by heterogeneities present in the medium between the source and the station.

The attenuation of S waves (${Q_S}^{-1}$) in Kanto area, Japan for the frequency range of 1.5 – 24.0 Hz was first attempted by [9]. Further studies on attenuation of direct P waves were attempted highlighting its importance in the evaluation of vertical ground motion at a particular site. In this present study, the extended coda normalization method [10] is used to determine the attenuation of P and S waves for Chamba region located in the north western Himalaya using recent earthquake records. The data collected used in the present work are based on earthquake events occurred during the period of 2009 to 2014. Obtained results are compared with the published results ([5], [11]) around these regions and are found matching.

TECHTONIC SETUP

The Himalayan belt is considered to be one of the seismically active regions of the world. The Indian plate is subducting under the Eurasian plate as a result of which this region is alarming seismicity. The relative velocity at which the Indian plate is subducting under the Eurasian plate is about 5cm/year in the direction of N13°E [12]. Three major thrust plane exists in the Himalayan belt. These are The Main Central Thrust (MCT), The Main Boundary Thrust (MBT), and The Main Frontal Thrust (MFT). As a result of this collision, the entire belt of Himalaya has experienced many great earthquakes including 1897 Assam EQ, 1905 Kangra EQ, 1934 Bihar-Nepal EQ and 1950 Assam EQ. Based on non-occurrence, a 750km long segment of the Himalayan belt between the eastern edge of 1905 Kangra EQ and western edge of 1934 Bihar-Nepal EQ rupture zone was identified as central seismic gap which is probable location of building up high strains [12]. Due to accumulation of high strain over a long period of time, a possibility of large magnitude earthquake remains there.

METHODOLOGY ADOPTED

Present work is based on the coda normalization method developed by [9] for the determination of quality factor. As per the method, the spectral amplitude of direct S waves are normalized by the coda wave amplitude. The coda window is considered after a fixed lapse time for all the data used for analyses. Lapse time should be greater than two times the arrival time of direct S wave (t_s). The spectral amplitude of coda wave at the above lapse time (t_C) is independent of hypocentral distance and propagation path as per [8]. This spectral amplitude of coda wave can be written as [10]

$$A_C(f,t_C)= S_S(f)P(f,t_C)G(f)I(f) \tag{1}$$

Where, f is the frequency under consideration, $S_S(f)$ is the source spectral amplitude of direct S waves, $P(f,t_C)$ is the coda excitation factor, $G(f)$ is the site amplification factor and $I(f)$ is the instrumental response. The coda excitation factor '$P(f,t_C)$' represents the decay in the spectral amplitude of coda wave with lapse time. For the case of direct S wave, the spectral amplitude however varies with hypocentral distance and is expresses as [10];

$$A_S(f, r)= R_{\theta\,\varphi}S_S(f)r^{-\gamma}\exp\left(-\frac{\pi f}{Q_S(f)V_S}r\right)G(f, \varphi)I(f) \tag{2}$$

Where, $R_{\theta\varphi}$ is the source radiation factor, $S_S(f)$ is the source spectral amplitude of direct S waves, γ is the geometrical spreading factor, $Q_S(f)$ is the quality factor for S wave, V_S is the average S wave velocity within hypocentral distance 'r' and φ represents the incident angle of S wave. Normalization of spectral amplitude of S wave by spectral amplitude of coda wave done by dividing eq. (2) by eq. (1) provided by [10];

$$\frac{A_S(f,r)}{A_C(f,t_C)}=R_{\theta\,\varphi}r^{-\gamma}\frac{G(f,\varphi)}{G(f)}\ P^{-1}(f, t_C)\exp\left(-\frac{\pi f}{Q_S(f)V_S}r\right) \tag{3}$$

Taking logarithm of eq. 3 as per [10] will give;

$$\ln\left(\frac{R_{\theta\varphi}^{-1}A_S(f,r)\,r^{\gamma}}{A_C(f,t_C)}\right) = -\frac{\pi f}{Q_S(f)V_S}r + \ln\left(\frac{G(f,\varphi)}{G(f)}\right) + \mathrm{const}(f) \quad (4)$$

For a fixed lapse time t_C, decay of coda wave amplitude is constant and hence $P(f,t_C)$ is also constant. Further, the effects of $R_{\theta\varphi}$ disappears once source characteristics are considered for large database [10]. In addition, the value of $\frac{G(f,\varphi)}{G(f)}$ becomes independent of incidence angle φ when number of records from various earthquakes are taken into account [10]. Hence, the simplified equation becomes as given in [10];

$$\ln\left(\frac{A_S(f,r)\,r^{\gamma}}{A_C(f,t_C)}\right) = -\frac{\pi f}{Q_S(f)V_S}r + \mathrm{const}(f) \quad (5)$$

Based on the above equation, the attenuation property of S waves $Q_S{}^{-1}(f)$ can be determined from the slope of the linear regression line drawn between $\ln\left(\frac{A_S(f,r)\,r^{\gamma}}{A_C(f,t_C)}\right)$ and. r. This will be average value of S wave attenuation for the entire region. The above method is further extended for the determination of P wave attenuation $(Q_P{}^{-1})$. For small magnitude range earthquake recorded within a narrow frequency range, ratio of spectral amplitude of P and S waves is constant as shown below [10];

$$\frac{S_S(f)}{S_P(f)} = \mathrm{const}(f) \quad (6)$$

Hence, considering eq. (1) and (6) following observation was made [10];

$$A_C(f,t_C) \propto S_S(f) \propto S_P(f) \quad (7)$$

Considering the above equation, the normalization of P wave amplitude $[A_P(f,r)]$ was done based on coda wave amplitude $[A_C(f,t_C)]$ similar to eq. (5) using the following equation [10];

$$\ln\left(\frac{A_P(f,r)\,r^{\gamma}}{A_C(f,t_C)}\right) = -\frac{\pi f}{Q_P(f)V_P}r + \mathrm{const}(f) \quad (8)$$

It can be observed from the above equations (5 & 8) that the values of A_S, A_P are functions of f and r. For region with known values of V_P and V_S, once the values of A_S, A_P and A_C are known, the values of Q_S & Q_P can be determined for different frequency ranges. Thus, it can be observed that these quality factors are dependent on frequency and increases with increasing frequency. This relation can be expressed as [2];

$$Q(f)=Q_0 f^n \quad (9)$$

Where, Q_0 is the quality factor at 1 Hz frequency and n is the frequency parameter defines the heterogeneity of the medium. Taking logarithm of eq. 9 as per [2];

$$\log\big(Q(f)\big) = n\log(f) + \log\big(Q_0\big) \quad (10)$$

Above equation represents a straight line equation between $log(Q(f))$ and $log(f)$ with n being the slope of the line and $log(Q_0)$ is the y intercept. Once the value of Q(f) is known for a wide range of frequencies (f), the values of Q_0 and n can be determined for P and S waves in a medium. Based on analyses attempted earlier, it was found that a low value of Q_0 in the eq. (10) represents high seismically active region while a high value of n indicates more heterogeneous medium. [3]

DATA & INSTRUMENTS

Ground motion records for past earthquakes (earlier to 1986) are very limited in India. In order to record ground motions, more than 250 strong motion instruments were installed throughout the Himalayan belt started with Jammu & Kashmir in the west to the Meghalaya in the east under the program of PESMOS (Program for Excellence in Strong Motion Studies). All the recording stations under PESMOS are maintained by the Department of Earthquake Engineering, Indian Institute of Technology Roorkee, India [13]. For the present work, ground motions recorded during various earthquakes are collected from PESMOS [13]. These ground motions were recorded by strong

Table.1 Seismic data records used for this study

Sl. No.	Origin Time	Lat. (Degree) N	Long. (Degree) E	Depth (km)	Magnitude (M_w)	Hypocentral Distance (km)
1.	31-01-2009 03:07	32.5	75.9	10	3.7	20.49
2.	17-07-2009 11:07	32.3	76.1	39.3	3.7	51.57
3.	02-10-2012 03:45	32.4	76.4	10	4.5	42.85
4.	02-10-2012 08:34	32.3	76.3	10	4.9	47.24
5.	03-10-2012 10:04	32.4	76.3	5	3.8	33.73
6.	03-10-2012 10:49	32.4	76.3	10	3.6	34.82
7.	03-10-2012 17:48	32.4	76.3	10	3.4	34.82
8.	06-11-2012 12:21	32.3	76.2	5	4.1	39.50
9.	11-11-2012 20:23	32.3	76.2	5	4	39.50
10.	17-06-2014 17:31	32.2	76.1	10	4.1	48.03
11.	21-08-2014 08:11	32.3	76.5	10	5	62.87

motion accelerographs which consists of internal AC-63 GeoSIG triaxial force balanced accelerometers and GSR-18 GeoSIG 18 bit digitizers with external GPS [12]. The recording of data in accelerometer is done in trigger mode at a sampling rate of 200 samples per second. The recordings are in ASCII format which is processed through a computer program to generate the output which is used in this study [12]. All the data used in the work are baseline corrected as per [12]. For the present work, ground motion record at Chamba station (latitude 32.555^o N & longitude 76.126^o E) are used for the analyses. Table 1 presents details about the recorded ground motions used in present work. A total of 11 ground motion record for different earthquakes are selected. These ground motion were recorded at stations located within hypocentral distance range of 20km to 65km around Chamba station as listed in Table 1. For all the ground motions considered, earthquake magnitude ranges from 3.0 to 5.0 (Mw). It has to be highlighted here (refer to eq.7) that for a small magnitude range, earthquakes occurred at different locations will have the same source spectral ratio for P and S waves within a fixed narrow frequency range [10]. The focal depths for all the ground motion records are within 50 km.

ANALYSES

As highlighted above, all the analyses are done for Chamba station. Based on the seismogram obtained from each of the ground motion records, P and S wave arrival time has been detected and the record for 3 second time window has been separated out from the onset of P and S waves separately. This separated ground motion signature have been filtered using Butterworth bandpass filter with pass bands of 0.5-1.5 Hz, 1-3 Hz, 2-4 Hz, 4-8 Hz, 5-10 Hz, 8-12 Hz, 10-15 Hz. Further based on the filtered data, the maximum positive peak to maximum negative peak amplitude is determined and half of that value is considered as $A_P(f,r)$ and $A_S(f,r)$ for P and S waves respectively [10]. For the case of coda waves, a time window of 3sec similar to the case of P and S wave is considered after a fixed lapse time (t_C) of 30secs for all the records. Lapse time (t_C) is considered from the earthquake origin time. This lapse time taken is longer than twice the S wave travel time (t_s) to make sure that no direct wave component has come into coda wave component [10]. In the analyses, $A_C(f,t_C)$ is considered as RMS amplitude of the filtered data obtained from coda window [10]. It has to be highlighted here that for the present analyses, P wave records are taken from vertical components of seismograph whereas S and coda wave records are taken from NS components in accordance with [5, 10].

For the analyses average value of P and S wave velocities (V_P and V_S respectively) are considered as 6.1 km/s and 3.5 km/s respectively as per [5]. Geometrical spreading factor γ of 1.0 is considered in the present analyses. The values of $\ln\left(\frac{A_P(f,r)\,r^{\gamma}}{A_C(f,t_C)}\right)$ and $\ln\left(\frac{A_S(f,r)\,r^{\gamma}}{A_C(f,t_C)}\right)$ are determined and plotted against hypocentral distance $'r'$ for each frequency band as shown in Fig 1(a-g) and Fig 2(a-g) respectively. It can be observed from Fig 1(a-g) and Fig 2(a-g) that all the plots are following a linear trend for frequency range of 0.5 to 15Hz for normalized P and S wave amplitude respectively. These linear trends are defined by the eq. 5 and 8. Using the slope of the regression lines i.e. $\left(\frac{\pi f}{Q_P(f)V_P}\right)$ and $\left(\frac{\pi f}{Q_S(f)V_S}\right)$, as per Fig 1(a-g) and Fig 2(a-g) respectively, the values of Q_P & Q_S values are obtained corresponding to the central frequency of each band. Further, in order to obtain the frequency dependent relationship, $log(Q_P)$ and $log(Q_S)$ are plotted against $\log(f)$ as shown in Fig. 3a and 3b for P and S wave respectively. From the linear relationship shown in Fig. 3a and 3b, the value of Q_0 and n are obtained for Chamba station as per eq. 10.

RESULTS AND DISCUSSION

Based on the analyses discussed in the last section, for 7 selected frequency range with central frequency from 1.0 to 12.5 Hz the value of Q_P found varying from 70 (1.0 Hz) to 1072 (12.5 Hz) and the value of Q_S is found varying from 134 (1.0 Hz) to 1384 (12.5 Hz). Summary of the results for all the frequency bands are presented in Table 2 separately. It is clear from Table 2 that both Q_P and Q_S depend on frequency. Further an increase in the value of Q_P and Q_S is seen with increase in frequency as shown in Table 2. In addition, the value of ${Q_S}/{Q_P}$ found in this study is greater than 1 for all frequency range

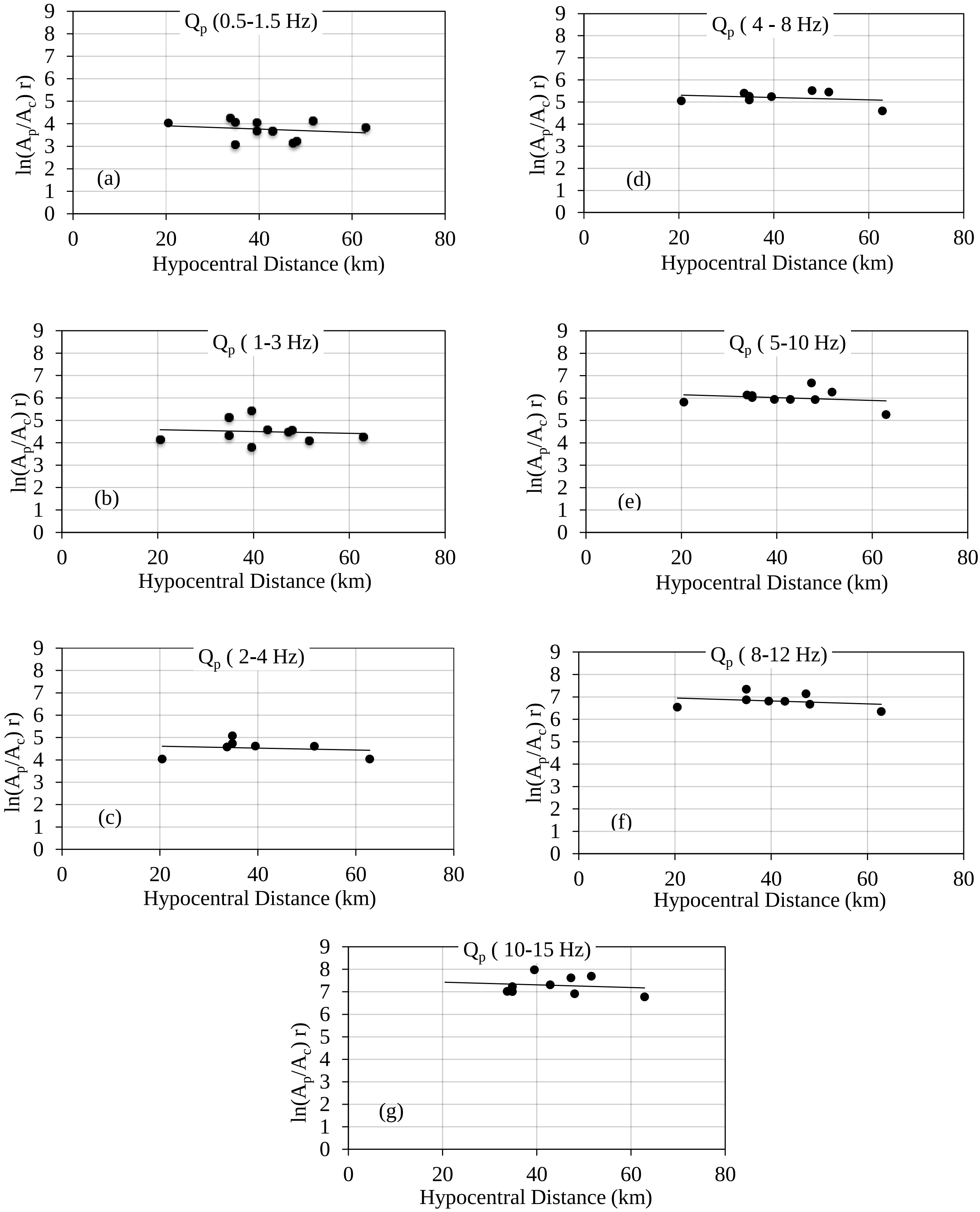

Fig. 1 Plot of coda normalized peak amplitude decay of P waves with hypocentral distance ($20 \leq r \leq 65$)

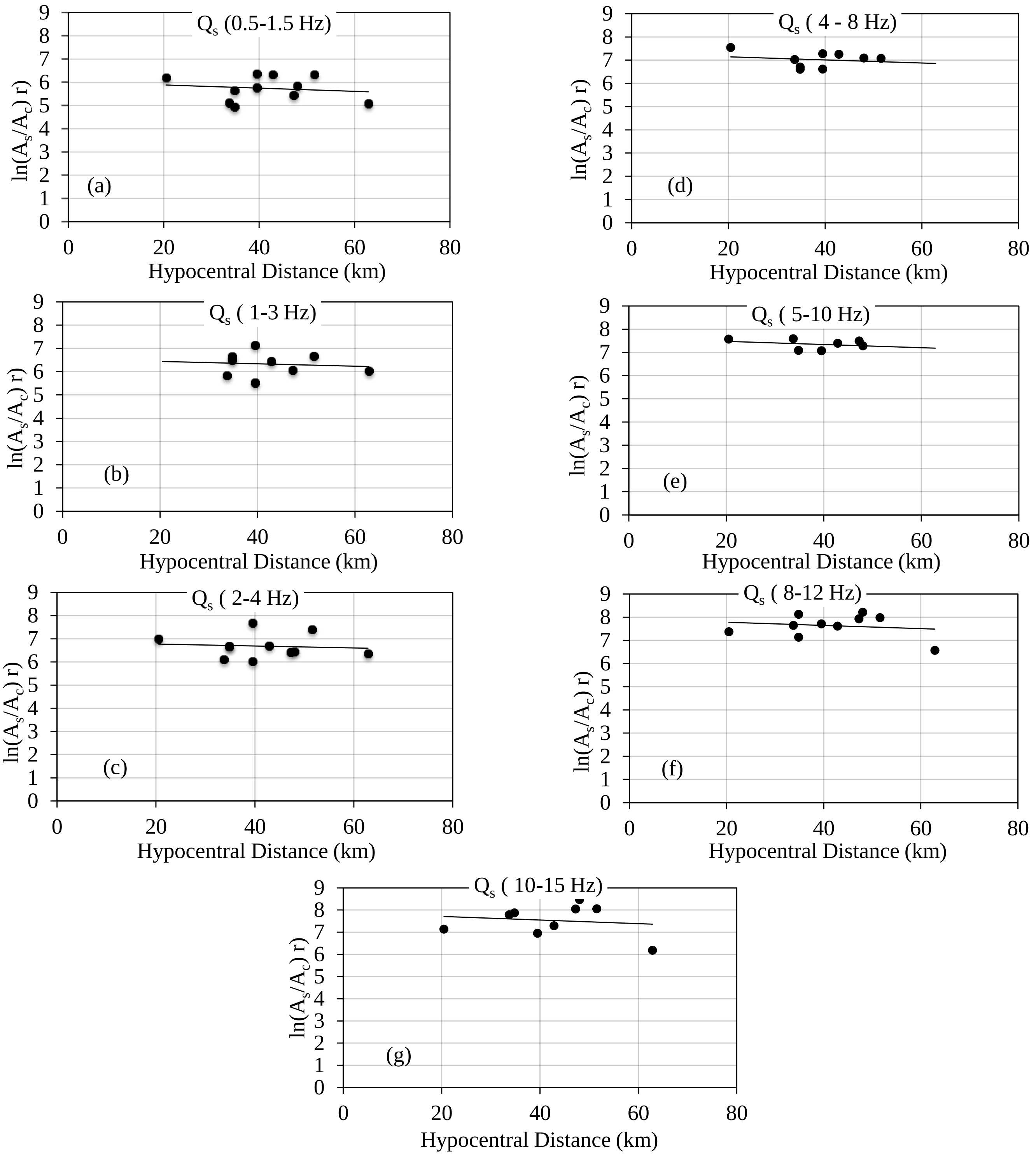

Fig. 2 Plot of coda normalized peak amplitude decay of S waves with hypocentral distance ($20 \le r \le 65$).

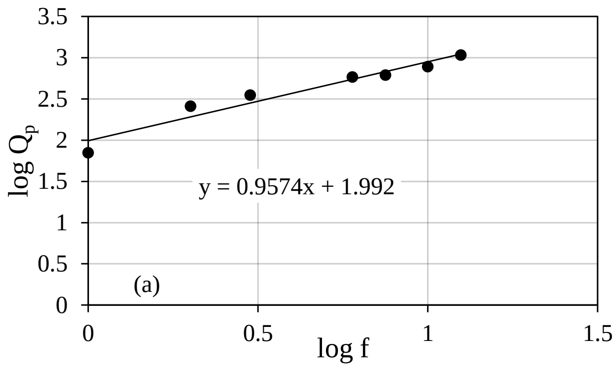

Fig. 3a Plot of $\log(Q_P)$ vs $\log(f)$ considering all the Q_P values obtained for 7 different frequency range.

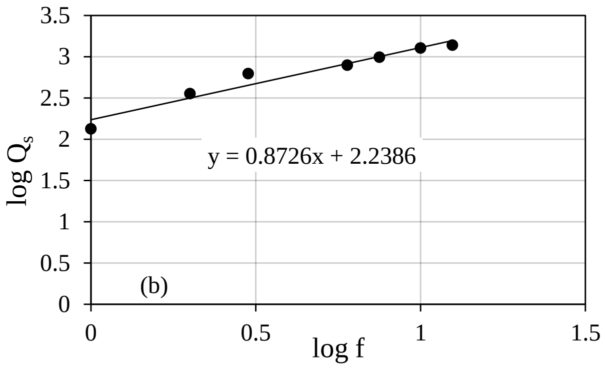

Fig. 3b Plot of $\log(Q_S)$ vs $\log(f)$ considering all the Q_S values obtained for 7 different frequency range.

Table 2. Q_P & Q_S values obtained for 7 frequency pass bands

Sl. No.	Freq. Band	Central frequency	Q_P	Q_S	$\frac{Q_S}{Q_P}$
1.	0.5-1.5	1.0	70	134	1.91
2.	1.0-3.0	2.0	257	359	1.40
3.	2.0-4.0	3.0	351	626	1.78
4.	4.0-8.0	6.0	583	792	1.36
5.	5.0-10.0	7.5	613	989	1.61
6.	8.0-12.0	10.0	780	1281	1.64
7.	10.0-15.0	12.5	1072	1384	1.29

and is close to ${V_P}/{V_S}$ [6]. Based on the laboratory results, the value of the ratio ${Q_S}/{Q_P}$ is less than unity for fully saturated rocks whereas larger than unity for dry rocks [5]. Results obtained from the present analyses also indicate the value of ${Q_S}/{Q_P}$ within the range 1.29-1.91. These ratios are also comparable with other published studies related to nearby region [5, 11].

Plot of $log(Q_P)$ and $log(Q_S)$ values with the $\log(f)$ is attempted in order to understand the frequency dependent relation and is found as $Q_P = 98f^{0.96}$ and $Q_S = 173f^{0.87}$respectively. The slope of the regression line gives the frequency dependent parameter n around 0.96 for P wave attenuation and 0.87 for S wave attenuation. The Q_o and n values estimated here suggests high seismic activity and less heterogeneity for Chamba region. In another work, [5] found the frequency dependent relationships for the Pathankot station as $Q_P = 103f^{0.99}$ and $Q_S = 139f^{0.95}$. The study area of Chamba (32.555ºN, 76.126ºE) considered in this work is close to the Pathankot area (32.45ºN, 75.76ºE), epicentral distance between two stations being 28.47 km and the results for these two stations are found matching closely.

CONCLUSIONS

The purpose of this study was to find the frequency dependent attenuation of P and S waves for Chamba region. Ground motion records from

11 earthquake events occurred from 2009 to 2014 are used for the analyses. The obtained result shows the attenuation of P and S waves similar for a frequency range of 0.5 to 15 Hz. Though P waves attenuates faster than S wave in low frequency range, their variation decreases with increase in frequency. It can clearly be seen from Table 2 that the Q_S/Q_P ratio is higher (1.91) for low frequency range (0.5-1.5 Hz) whereas the value of Q_S/Q_P ratio becomes 1.29 which is closer to unity in higher frequency range (10-15Hz). Obtained results are in good accordance with other published results hence it can be useful for further studies in ground motion prediction in that region.

All the selected 11 earthquakes of small magnitude occurred within focal depth of 10 km. In the future, further studies can be performed considering events of large magnitude earthquakes occurred at deeper depths. Further, in the present study only low frequency band is considered to understand the attenuation of P and S waves. It will be interesting to see how the attenuation characteristics changes for high frequency range.

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