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RESEARCH ARTICLE

A reappraisal of Attenuation of Seismic Waves and its relevance towards Seismic Hazard

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Abstract

The evaluation of attenuation of seismic waves in a seismically active region plays an important role in risk studies. Generally, damages are resulted from the amplitude of waves originating from the earthquake source, which are highly dependent on attenuation property of the medium. Therefore, the good knowledge of attenuation is the first step for obtaining a better understanding of source spectra as inferred from seismograms. Understanding the attenuation property of a medium gives important signs to design suitable preventive measures to minimize seismic hazard in a region. Full information on seismic wave attenuation has been desired to investigate the structure of the interior of the earth and to predict strong earthquake ground motion in engineering seismology.

Effect of medium characteristics on earthquake waves

The decay of seismic wave amplitude with distance defines the attenuation of the medium as shown in Figure 1. Attenuation is commonly described by the quality factor Q, which is the combination of intrinsic attenuation, due to the conversion of mechanical energy into heat (Aki, 1980) and scattering phenomena due to heterogeneities in the medium related to folding, cracks and impedance contrasts. Several studies on attenuation by several researchers conclude a linear dependence of Q on frequency between 1 to 25 Hz (Aki, 1980 & Aki, 1981). The dependence of Q on frequency is a general feature. The temporal and spatial variation of seismic wave attenuation has also been used as an earthquake precursor. The attenuation studies have been done for a number of regions in world by several investigators (Aki & Chouet, 1975; Martynov et al., 1999; Dominguez et al., 1997; Takemura et al., 1991; Scherbaum & Sato, 1991; Steensma & Biswas, 1988). In India a number of studies have been observed to estimate seismic wave attenuation (Gupta & Rambabu, 1994; Mandal & Rastogi, 1998; Mandal et al., 2001; Gupta et al., 1995; Sharma et al, 2007; Sharma et al, 2008; Sharma et al, 2009; Sharma, 2014). Attenuation is attributed to several factors, which are geometrical spreading, intrinsic attenuation and scattering. Non-dimensional parameter Q is used to measure the attenuation properties in a region. The seismic wave attenuation can be estimated by determining the quality factor for P and S waves (Q_α and Q_β), for surface waves and for coda waves (Q_c).

Attenuation of seismic waves

An earthquake is accompanied by release of the elastic energy that propagates in the form of seismic waves through the earth's crust, mantle and core. The decay loss of energy of seismic waves with increasing distance from the source is known as seismic wave attenuation. The extent of energy losses depends upon the type of source and physical properties of the medium. The observed seismic wave amplitudes usually decay exponentially with increasing travel distance and decay rates are proportional to Q^{-1}, which characterizes the attenuation. The amplitude of the seismic wave decreases with the distance traveled as a result of certain factors given below:

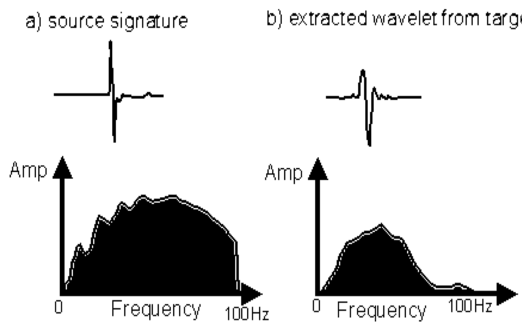

Figure 1: (a) The wavelet obtained at the source in case of an earthquake. (b) The extracted wavelet from the target received at a recording station.

(a) Geometrical spreading

Waves are spreading from any source of finite dimensions, which decreases in the amplitude due to the increase of the area of the wave front. Even in the homogeneous and elastic particle motion is generally attenuated during propagation due to the expansion of the wave of the wave fronts; this is the geometrical spreading or attenuation by spreading. In the elastic media a given point, for a harmonic component with angular frequency ω, the particle motion can be written as,

$A = A_0 \exp(j\omega t)$ ————(1)

The energy per unit volume, or intensity, is

$E = 1/2\ \rho\omega^2 A_0^2$ ------------(2)

where ρ is the rock density and A_0 the maximum particle displacement.

In geometrical spreading, the energy per unit volume decreases as a function of the distance of the wave from the source. With the point source in the homogeneous media, the wave surfaces are spheres, and the ratio of the intensities at two distances from the source is written as,

$E_2/E_1 = (r_1/r_2)^2$ -------------(3)

e ratio of the particle motion $A_2/A_1 = (r_2/r_1)$ and the particle motion due to geometrical spreading is proportional to the distance traveled by the wave as shown in figure 2. The amplitude is attenuated according to an inverse law 1/r. In heterogeneous medium, the wave surface is not spherical and the ratio of intensities at distance r_1 and r_2 from the source is no longer $(r_1/r_2)^2$.

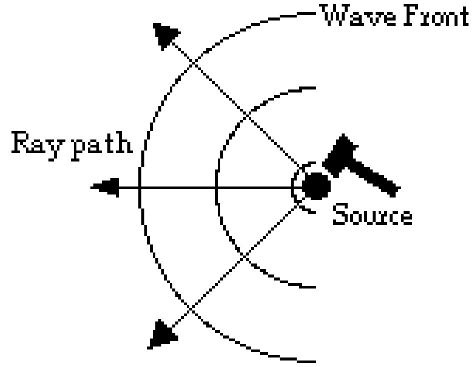

Figure 2: Illustration of wave front and ray path in case of an earthquake.

(b) Absorption

Intrinsic attenuations described loss of energy to heat or other forms of energy due to anelasticity of the medium. Due to this elastic energy get absorbed in the medium. Many proposed mechanisms are based on the observation that crustal rocks have microscopic cracks and pores, which may contain fluids. These features have dimensions much smaller than the wavelengths of regional seismic phases. Unless the transmitting medium is perfectly elastic, mechanical energy is withdrawn from each passing waves and converted into another forms such as heat. This occurs in a large variety of ways. The processes are collectively called absorption. If the medium is not perfectly elastic, which is often the case in the subsurface, the seismic waves undergoes some dissipation, part of the seismic energy being converted irreversibly into heat. This process is called absorption as shown in figure 3. Absorption is related to the frequency of the seismic waves as the rule, the higher the frequency the greater the absorption.

Let us consider a plane wave propagating at velocity v in a homogeneous, isotropic and elastic medium in a positive Z direction. The movement of a harmonic component can be written as follows:

$$A=A_0\exp(j\omega(t-z/v)) \qquad \text{--------------}(4)$$

If the medium is homogeneous, isotropic and inelastic, the motion is as:

$$A=A_0\exp(j\omega(t-z/v))\exp(-\alpha z) \qquad \text{-------------}(5)$$

where α is defined as the 'absorption coefficient', the absorption coefficient can be considered as the first approximation as proportional to the frequency.

$$\alpha=\pi f/Qv \qquad \text{--------------}(6)$$

where f is frequency, v is wave velocity and Q is quality factor.

Quality factor measure the deviation from perfect elasticity (Knopoff, 1964) as given below:

$$2\pi/Q=-\Delta E/E \qquad \text{---------------}(7)$$

where ΔE is the energy loss in one cycle and E is the total energy in a harmonic wave.

The reciprocal of Q i.e. 1/Q is a measure of the attenuation in the medium. This can be represented as the combination of intrinsic attenuation (Qi) and scattering attenuation (Qs), by the following expressions (Dainty, 1981).

$$1/Q=1/Q_i+1/Q_s \qquad \text{---------------}(8)$$

Although it is difficult to separate out the relative contribution of intrinsic attenuation and scattering attenuation from seismic wave attenuation but still efforts are being done to study the contribution of intrinsic and scattering attenuation of the measured total attenuation.

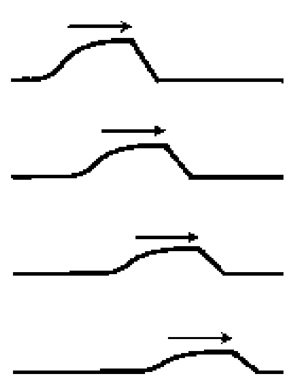

Figure 3: Illustration of absorption with in the medium as wave approaches in the medium the amplitude of the wave is decreased.

(c) Scattering

Scattering due to heterogeneities distributed in the Earth also causes a decrease in the amplitude with travel distance (Aki, 1980). It is mainly the redistribution of energy in real sense in the medium due to various heterogeneities. Kikuchi (1981) studied scattering by distributed cracks and cavities. If the medium through which the waves are passing is not uniform in physical properties, the energy splits into two, the reflected and the refracted pulses at each boundary. If the many interfaces are closely spaced or are irregular in shape, the effect is to produce many subdivisions of the initial pulse traveling in the variety of directions, then the energy is said to be scattered. Such type of wave attenuation is called as scattering as shown in figure 4. Scatter tends to spread the energy in time as well as in the space. The modification of the seismic wave caused by the three-dimensional heterogeneous is broadly called seismic wave scattering. Sato (1977) studied energy propagation including scattering effects.

The seismic wave scattering is the process in which a primary wave interacts with heterogeneity of the medium and produces new secondary waves. This oversimplified description can be applied to many different physical fields, but every case presents some peculiar characteristics. The seismic case can be better understood if the different elements, which take part in the phenomenon, are considered. The adopted starting point supposes a seismic wave traveling in the medium. P and S waves are particularly interesting because they are considered to make up the major part of local events. Although Knopoff and Hudson (1964) showed that P to S and S to P conversions can be neglected, when high frequencies are considered. The medium where the scattering takes place can be basically considered as homogeneous or heterogeneous. In the first case discrete obstacles such as cracks, faults, low or high density and low or high velocity are considered inside the homogeneous medium. Aki (1969), Aki and Chouet (1975), Dainty (1981) and Kikuchi (1981) for instance have used this discrete model with a random uniform distribution. If the medium is taken as heterogeneous, the scattering field is treated as a continuous medium where inhomogeneous wave equations should be solved. The problem may become extremely complicated. An approach to this case is considering a 'random medium' that is, a space with average characteristics in which deviation from these means values produce random heterogeneities. The fluctuating parameters may be the velocity density or the Lame parameters.

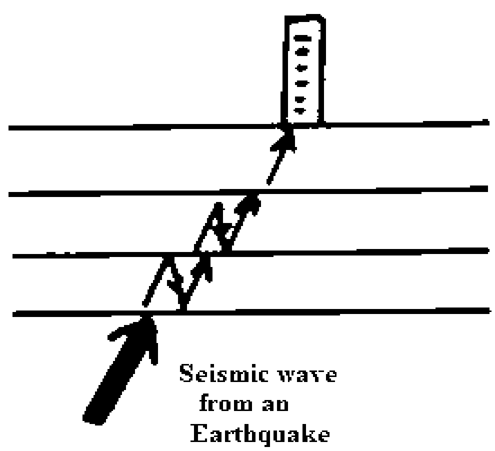

Figure 4: Seismic wave from an earthquake undergoes scattering through various layers or heterogeneities.

The seismic wave scattering is very much depends on the size of the heterogeneity with the inhomogeneity scale length 'a', 'k' is the wave number and 'λ' is the wavelength, 'ka' constitutes an important parameter. If ka<<<1 or ka>>>1 the waves are not affected by the obstacle and the medium acts like the homogeneous body. The scattering effects are most significant (Wu and Aki, 1988). The incident power is scattered to different directions with large angle to the incident direction. This case is frequently met in many physical situations. Scatterer believed to be the principal cause of attenuation of seismic waves at short distances. Due to inhomogeneous nature, geological media act as the scatterer for the waves traveled in the Earth medium. In the deep interior of the Earth it is very small and is often neglected in the deeper studies. Scattering, reflection, diffraction etc. are the main dissipation of seismic waves.

Importance of attenuation

Study of seismic wave attenuation in the high frequency range (1 to 30Hz) is emerging as one of the fundamental requirements to understand seismotectonic setup for a seismic region and also to model the strong ground motion for a seismic region. Many researchers have worked to find the attenuation characteristics of various regions by estimating the parameter quality factor for the respective regions (Yoshimoto et al., 1993; Gupta et al., 1998; Mandal et al., 2001, Mandal & Rastogi, 1998 etc.). The study of attenuation is important because of the following:

- It provides the information about the medium characteristics such as physical properties of the material and also the inhomogeneities level of the medium.
- For applying the path correction during the composition of P and S wave spectra for the estimation of earthquake source parameters.
- To estimate the strong ground motion at an engineering project site from the probable earthquake source zone identified in the region.
- It is also needed in the seismic hazard estimation of a region.

Quality factor “Q” is interpreted as a tectonic parameter and is a good indicator of the stress state therefore, temporal and spatial changes in “Q” in a given seismic region may be used as an earthquake precursor. The quality factor is a function of frequency and its value increases with increasing frequency.

The amplitudes of earthquake ground motion at observing sites are influenced by the source characteristics, travel path and local site conditions. The effects of travel path on earthquake ground motion are linked to attenuation of propagating seismic waves. Therefore the study of attenuation of seismic waves is essential for simulation of earthquake ground motion and seismic hazard analysis in a region. The attenuation properties of the media are inherent elements governing the amplitude of seismic waves at various distances from an earthquake source. The overall attenuation is composed of several factors that include geometrical spreading, scattering due to inhomogeneities in the media and anelasticity. The geometrical spreading controls the amplitudes of seismic waves in the homogeneous and purely elastic earth.

As the real earth is not perfectly elastic the net loss of energy during seismic wave propagation is symbolized by absorption. The absorption of seismic wave is partly controlled by intrinsic physical loss mechanisms such as internal friction and partly by inhomogeneities along the travel path that can cause scattering. Due to the non-elastic nature of the medium, a part of the energy in the wave is dissipated instead of being transferred through the medium. This type of attenuation of seismic waves is described by a parameter called quality factor, Q. The attenuation of seismic waves in a region can be studied by determining the quality factor, Q, of that region.

In addition to the attenuation of seismic waves due to physical loss mechanisms, the amplitudes of earthquake ground motions can be increased or decreased by the near surface material through which the seismic waves propagate. The configuration of the underlying material also affects the amplitude of the seismic wave. There is increase in the amplitude as the upwardly propagating seismic wave traverses the decrease in the impedance. Figure 5 presents the different types of seismic waves in a local seismogram. The arrival of coda wave is considered to be twice of the arrival time of the S wave ad shown in figure 5.

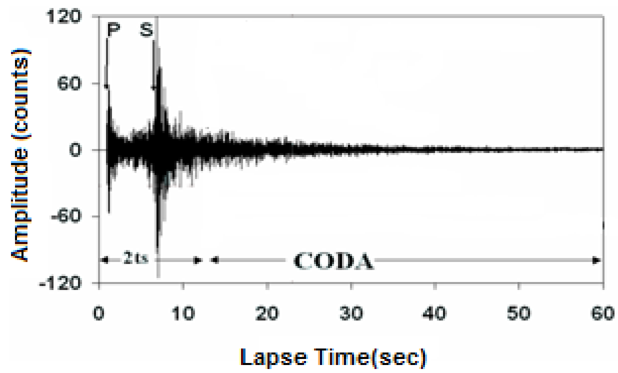

Figure 5: P wave, S wave and coda waves shown in a local seismogram.

Seismotectonic relevance of Attenuation

The attenuation of seismic waves by estimating the quality factor, Q, has been well studied for the various regions of the world. The first estimates of coda Q were made by Aki and Chouet (1975) in the Japan. They found that coda Q in these regions is strongly frequency dependent and increase with increasing frequency. The same increase of coda Q with that of increasing frequency was observed in different regions around the world (Cathrine, 1990; Mayeda et al., 1992; Mandal et al., 2001; Gupta et al., 1995 etc.). Coda Q was found to be one of the geophysical parameters, which best correlated with the level of tectonic activity. In tectonic active regions coda Q is high and show strong frequency dependence, whereas in stable regions coda Q is low and show weak frequency dependence. An increase in coda Q with the age of oceanic crust was also been observed by Jin et al.(1985). The temporal variation of coda Q is another important topic, which attracted a lot attention among seismologists. Chouet (1979) first noted a marked increase in the energy of coda waves of earthquakes of similar magnitudes and locations. He suggested two possible mechanisms based on temporal variation in the source spectra of earthquakes and on changes in scattering properties of the crust. Following his work there have been many studies on the temporal changes of coda Q in searching for a precursory phenomena before a major earthquake. In most of these results, it was found that the mean value of coda Q anomalously higher for a certain period of time prior to main shock and decreased after the main shock.

Aki (1980) obtained the frequency dependent Q_β for Kanto area, Japan using the coda normalization method. Sato & Matsumura (1980) applied this method to a data set of deep borehole observation. The Q_β has been estimated from the array analysis of strong motion data (Takemura et al., 1991). Yoshimoto et al.(1993) has proposed a new method for the simultaneous measurement of Q_α and Q_β by extending the coda normalization method. Del Pezzo et al. (1995) measured intrinsic and scattering seismic attenuation in the crust.

There are few studies which simultaneously estimated the frequency dependent Q_β and Q_α in the world (Hough and Anderson, 1988; Masuda 1988; Campillo & Planet, 1991). Sekiguchi (1991) estimated attenuation of P-waves in the Kanto Tokai area and gave the frequency independent Q_α^{-1} and $Q_\alpha^{-1}/Q_\beta^{-1}$ as 4/9. $Q_\alpha^{-1}/Q_\beta^{-1}$ are equivalent to Vp/Vs is the outcome of Rautian et al. (1978) for the Gram region. Yoshimoto et al. (1993) extended the coda normalization method and estimated frequency dependent quality factor for P and S-waves by means of extended coda normalization method for Kanto region, Japan. Benett & Bakun (1982) estimated depth dependence of quality factor for S-waves beneath the Kanto area. Several studies are reported to estimate Qc for various regions in the world and India (Mandal and Rastogi, 1998; Paul et al., 2003; Gupta & Ashwani, 2002; Catherine, 1990; Wong et al., 2001; Gupta et al., 1996; Pulli, 1984; Kumar et al., 1997; Ambeh & Fairhead, 1989; VanEck, 1988). Der(1998) studied high frequency P and S-wave attenuation in the Earth.

Attenuation of P and S-waves in Tonga region are studied by Flanagan & Wiens (1998) and reported that Q_α and Q_β are low in the upper 200 km and Q appears to increase rapidly with depth. Gupta et al. (1998) for Koyna region, India observed lapse time dependence of Q_c. It is interpreted that as the lapse time increases the quality factor Q_c also increases. Q_c and Q_β estimates in the Garhwal Himalaya using strong motion records of Uttarkashi Earthquake are reported by Gupta & Kumar (1998). Dutta et al.(2004) showed that Q_β is less than Q_c for frequencies between 0.6 to 3 Hz and high for frequencies greater than 3 Hz for Central Alaska region. Oceanic Coda waves and S-waves are attenuated by the same mechanism and they sample the same regions in the lithosphere (David & Casanova, 1989). Attenuation study of P and S-waves studied by Patane et al. (1994) for Itly, which show that quality factor using S and P-waves increases with frequency. Frequency dependent attenuation of high frequency P and S waves in the upper crust in Western Nagano, Japan are estimated by Yoshimoto et al. (1998). Coda Q is estimated in the Mount Cameroon volcanic region, west Africa by Ambeh and Fairhead (1989). Attenuation of coda waves is being studied by Pulli, 1984 for New England.

Crustal Q_β in the Ganga Basin for the 1988 Nepal- India border Earthquake is observed by Dinesh (2005) showing frequency independent value of Q_β estimated as 1250. The estimation of coda-Q and Q_β using strong motion records are available for various Indian regions (Gupta et al., 1995; Gupta and Ashwani, 1998; Gupta et al., 1998; Gupta and Ashwani, 2002 and Mandal et al., 2001). Frequency independent Q for Garhwal Himalaya using the accelerograms of 1991 Uttakashi earthquake and 1999 Chamoli earthquake are estimated by Dinesh et al.,(2005, 2006). Some studies have also been done using strong motion records for Koyna region (Gupta and Rambabu, 1994) and for Garhwal and Himachal regions (Chandersekran and Das, 1994). Strong correlations between the degree of frequency dependence and the level of tectonic activity in the area of measurement have also been made by several researchers for a number of tectonic regions (Aki, 1980; Pulli & Aki, 1981; VanEck, 1988). They ascertained higher n values for tectonically active regions as compared to that of tectonically stable regions. The values of Q_0 vary from 11 to 166 and n varies from 0.49 to 1.85 (Mandal & Rastogi, 1998).

Singh et al.(2004) have estimated a relation $Q=800f^{0.42}$ for the Indian shield region. Mandal and Rastogi (1998) obtained a relation $Q_c=169f^{0.77}$ for the Koyna region using the digital seismograms of 30 earthquakes recorded on one to three stations. Gupta et al. (1998) have estimated the relation $Q_c=96f^{1.09}$ for same region using 76 seismograms from 13 earthquakes. Fortunately, adequate scientific knowledge exists allows in making realistic simulation of the behavior of the solid earth system through the computation of increasing realistic seismograms with broad frequency content. Attenuation is merely a reduction in amplitude or energy caused by heterogeneity and anelasticity in the earth. The attenuation can be defined by the inverse of the dimensionless quality factor Q which is a ratio of stored energy to dissipated energy during one cycle of the wave (Jhonson and Toksöz, 1981). The attenuation is a petrophysical parameter, which is more sensitive to the lithology and physical properties (pressure, temperature, saturation with fluid and gas etc.) than to velocity (Toksöz et al., 1978). Characteristics of seismic attenuation in two tectonically active zones of Southern Europe are studied by Del Pezzo et al. (1991). Attenuation in Southeastern Sicily, Italy are estimated by Giampiccolo et al. (2002).

Using single backscattering model Gupta et al. (1995) estimated frequency dependent Q_c from seven local earthquakes of the Garwal Himalaya. The frequency dependence average Q_c relation ($Q_c=Q_of^n$) has been obtained as $Q_c=126f^{0.95}$, which indicates that the attenuation at high frequency is less pronounced. Mandal et al. (2001) used the scattering method of Aki and Chouet (1975) to compute coda Q_c for 48 small local earthquakes of magnitude ranging from M_w 2.5 – 4.8. In this study Q_o and n are estimated to be 30±0.8 and 1.21 ± 0.03, respectively. It has been inferred that north of MCT is found to be more attenuative in comparison to the region south of MCT (Mandal et al., 2001). Although the spatial distribution of frequency dependent coda Q_c relation have been given by Mandal et al. (2001). Simultaneous estimation of Q_α and Q_β using the extended coda normalization method on local earthquake data for any Indian region has not been reported so far in the literature. The estimation of coda-Q and Q_β are available for Indian various regions (Gupta et al., 1995; Gupta and Ashwani, 1998, Gupta et al., 1998; Gupta and Ashwani, 2002; Dinesh and Khattri, 1999).

Mandal (2006) estimated the Q_β vs. Q_α relation for the Kachchh rift zone using the Sp converted phases on the accelerograms. He estimated that the ratio Q_β/Q_α lies in between 0.41 to 2.99 in Kachchh region. Also Padhy, 2009 estimated $Q_\beta/Q_\alpha \geq 1$ for Bhuj region. A comparative study of attenuation of seismic waves for Chamoli, Kachchh and Koyna regions of India has been evaluated by Sharma, 2014 and found $B_0 > 0.5$ for Chamoli while $B_0 < 0.5$ for Kachchh regions. This represents that scattering attenuation is predominant over intrinsic attenuation for Chamoli region of India. For Kachchh region intrinsic attenuation is predominant over scattering. Vassiliou et al. (1982) have given general observations of Q_β and Q_α relations in sedimentary rocks. $Q_\beta = Q_\alpha$ for dry rocks, $Q_\beta \geq Q_\alpha$ for partially saturated rocks and $Q_\beta \leq Q_\alpha$ for fully saturated rocks. For Indian regions like Chamoli, Kachchh and Koyna region the attenuation studies carried out by the Sharma et al (2009), Sharma et al (2008) and Sharma et al (2007) show the $Q_\beta \geq Q_\alpha$ which represents the partially saturated rocks in these areas. Figure 6 shows the value of attenuation parameter with respect to the frequency for various regions worldwide. A modest approach to describe the attenuation of seismic waves can be done if we relate the attenuation parameter with the velocity of the wave. It can be easily described as we know the attenuation parameter is inversely proportional to the velocity of the seismic wave.

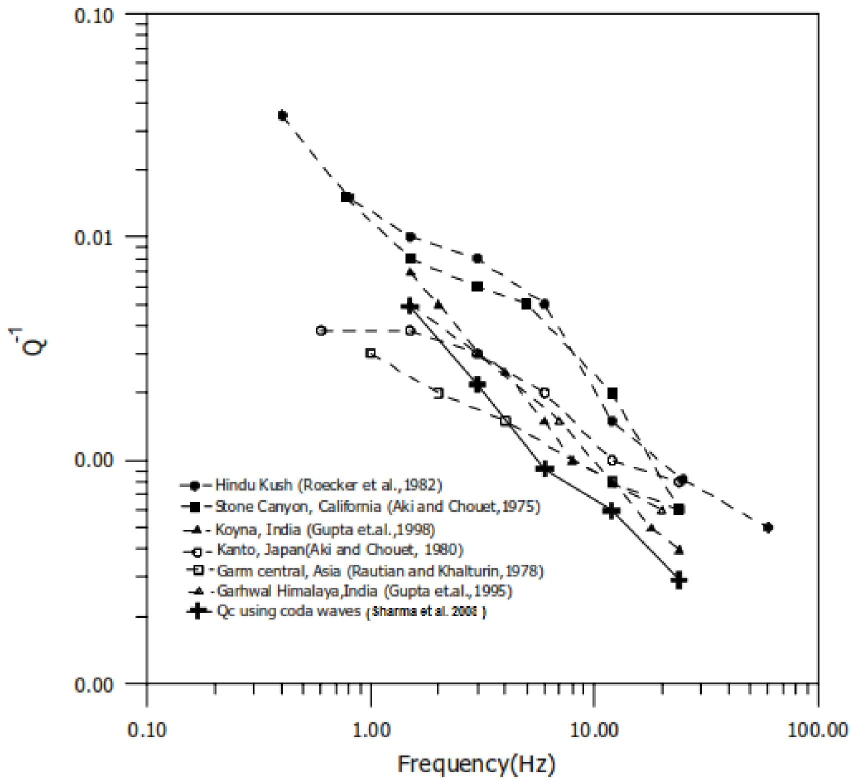

Figure 6: Decay of Q^{-1} values as the frequency increases for various regions worldwide (modified after Sharma et al, 2008). Sharma et al, 2008 study is for Kachchh region Gujarat.

Attenuation is attributed to several factors, which are geometrical spreading, intrinsic attenuation and scattering. Non-dimensional parameter Q is used to measure the attenuation properties in a region. The seismic wave attenuation can be estimated by determining the quality factor for P and S waves (Q_{α} and Q_{β}), for surface waves and for coda waves (Q_c). The earthquake waves after originating from the source at depth are affected by the medium through which they travel as well as by the site characteristics at the surface. Therefore the medium as well as site characteristics play an important role in controlling the levels of ground motions and thus affect the ground motion in a region.

Conclusion

The evaluation of attenuation of seismic waves in a seismically active region plays an important role in risk studies. Generally, damages are resulted from the amplitude of waves originating from the earthquake source, which are highly dependent on attenuation property of the medium. Therefore, the good knowledge of attenuation is the first step for obtaining a better understanding of source spectra as inferred from seismograms. The decay of seismic wave amplitude with distance defines the attenuation of the medium. Attenuation is commonly described by the quality factor Q which is the combination of intrinsic attenuation, due to the conversion of mechanical energy into heat and scattering phenomena due to heterogeneities in the medium related to folding, cracks and impedance contrasts. Many works done on attenuation by several researchers conclude a linear dependence of Q on frequency between 1 to 25 Hz. The dependence of Q on frequency is a general feature. Understanding the attenuation property of a medium gives very important input to design suitable preventive measures to minimize seismic hazard in a region. Full information on seismic wave attenuation has been desired to investigate the structure of the interior of the earth and to predict strong earthquake ground motion in engineering seismology.

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