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VSP P-wave attenuation model study in elastic earth: spectral ratio method vs centroid frequency shift method

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Summary

Seismic attenuation is potentially an important quantity to characterize lithology and other petrophysical properties of reservoir. For attenuation analysis in this paper near zero-offset 2-dimensional VSP seismograms have been generated on different layered earth media by using elastic finite difference modeling. Vertical seismic profile (VSP), plays an important role in understanding the reservoir due to one-way travel path of propagating seismic waves into the earth media. In VSP's, energy travels only one way through the earth media and the frequency component of the VSP signals are attenuated less than those of reflection seismic and contains better signal-to-noise ratio in data at higher frequencies. In this study two different methods, spectral ratio (SR) and centroid frequency down shift (CFD) methods have been applied to estimate the attenuation of compressional waves propagating through different layered earth media. The model based attenuation analysis of different depth intervals and different frequency ranges also been examined to validate the sensitivity of attenuation measurements. Implementation of both of these attenuation estimation techniques plays a very efficient role to measure attenuation factor on various model VSP seismograms. We find attenuation analysis results of CFD method is more robust than that of SR method over all the attenuation models because CFD method takes a statistical average over the entire frequency band width and it is comparatively less sensitive to reflection and transmission of energy, divergence effect and scattering of energy.

Key words: Attenuation factor; centroid frequency down shift method; spectral ratio method; VSP

Introduction

Seismic attenuation or frictional energy loss per cycle (Aki and Richards,1980) in a propagating waveform through the earth media is an important parameter of subsurface, and can provide information about rock layers. It has been long believed that attenuation is an important quantity for the characterization of rock and pore fluid properties, e.g. saturation, porosity, permeability and viscosity because amplitude attenuation is more sensitive than velocity (Best et al.,1994). Measurement of both velocity and attenuation provide complementary information about rock properties and combined use of velocity and attenuation data in seismic analysis provides greater insight into the rock formation and rock can be described in terms of a dimensionless quantity, the quality factor Q or attenuation factor Q^{-1}. In practice determination of Q is much harder because the wave amplitude is highly sensitive to noise, scattering, receiver coupling effect or interference from other signals. It is necessary take extra care in processing and prepare the data for Q estimation. The downgoing waveform in a VSP data set provides direct observation of the changing nature of wavelet as it propagates through the earth media. The attenuation estimation of a seismic wave with a borehole seismic imaging technique such as VSP is more effective than with surface seismic data. This is because VSP energy travels short paths (i.e. travel only one-way) through the earth media, such that high frequency components of the VSP signal are attenuated less than those of the surface seismic signal. VSP data usually contains high frequency and have better signal to noise ratio at higher frequencies than do surface seismic data. The propagating seismic waves from source point to receiver positions are affected by different changes in amplitude, phase or frequency as a function of propagating medium. Seismic attenuation of propagating wave energy through the heterogeneous earth media varies with its different layer properties such as pore geometry, mineralogical composition, the pore fluid content and its responses to rocks. The elastic absorption which depends on pore fluid type, its degree of saturation, confining pressure, connectivity and porosity has been demonstrated in the laboratory (Toksoz et al.,1979; Winkler and Nur,1979). Spectral Ratio (SR) method (Tonn,1991; Matshushima,2007) and Centroid Frequency Down Shift (CFD) method (Quan and Harris,1997) have been used in this study to estimate compressional wave (P-wave) attenuation of model near zero-offset VSP in elastic isotropic layered earth media. Q is an useful parameter because of its sensitivity to layer properties such as lithology, porosity and pore fluid characterization (Dasgupta and Clark,1998). There are wide variety of Q estimation technique including laboratory based measurement of Q and its dependence on parameters such as lithology and gas saturation (Frisillo and Stewart,1980) have been made on high frequency level. There are many others who have perfromed laboratory based attenuation measurement including Frisillo and Stewart (1980), Toksoz et al., (1979), Winkeler and Nur (1979).

Numerical finite difference methods have been widely used to model seismic wave in elastic media, because of their ability to accurately model seismic wave in heterogeneous media (Bohlen,2002). Inversion based methods include the work of Amundsen and Mittet (1994) for a layered media with a complex velocity. They show good results for Q recovery when Q-values are less than 50. Here in this study we start with a brief review of seismic modeling and attenuation measurement theory especially SR and newly developed CFD methods. Next we performed different model based validity tests on various layered earth media with different levels of attenuation. Finally we summarized the comparative attenuation analysis result of SR and CFD methods on various model near zero-offset VSP in layered earth media.

Theory and/or Method

Attenuation estimation was perform for near zero-offset VSP seismograms have been generated on simple flat layered earth models by using finite difference modeling of isotropic elastic wave equation. In this study we applied the absorbing boundary condition in the sides of the models, and a reflecting free surface boundary condition on the top edge (Fig. 1). The source signature shown in the Fig.2, is a single Ricker wavelet with 50Hz. dominant frequency. The computation of all the 2D seismic models in this study typically involves the use of a point source. Using such a simple model is a good idea to understand the behavior of propagating seismic waveform (Fig. 3). This initial simple model will not produce any reflected and transmitted events since it is a single homogeneous solid. A seven point median filter was applied to flattened and separate the downgoing events from the total wavefield. Following the median filtering a zero phase bandpass filter (5,10-70,150Hz.) used to remove the ambient noise.

In this study attenuation estimation was done by spectral ratio (SR) method and centroid frequency downshift (CFD) method.

Spectral Ratio Method**:** Spectral-ratio method is the best known technique for Q computation described by (Bath,1974), and (Tonn,1991).This method is based on the assumption that the ratio of seismic amplitude spectra at two different depths varies as a function of frequency.

$$\frac{A_2(f,z_2)}{A_1(f,Z_1)} = e^{-\frac{\pi f \Delta t}{Q}} C \qquad (1)$$

A_1 and A_2 are the amplitude spectra of seismic signal at z_1 and z_2 depth levels, α attenuation coefficient related to the inverse of quality factor Q as $\alpha = Q^{-1} \pi f/V$. Now taking the logarithm of both sides of equation (1), we get the explanation of spectral ratio as:

$$\ln\left|\frac{A_2(f,z_2)}{A_1(f,Z_1)}\right| = -\frac{\pi f \Delta t}{Q} + C$$

(2)

The equation (2) states that logarithmic ratio of amplitude at two different depth levels is a linear function of frequency and the equation (2) can be rewritten as:

$$Y = C + (m)f \tag{3}$$

A linear regression of the left hand side of equation (2) versus frequency therefore yields a slope, m that is equal to $-\pi\Delta t/Q$, and C is a single constant value. The slope m of the linear equation (3) yields the Quality Factor, Q as:

$$Q = -\frac{\mu f \Delta t}{m} \tag{4}$$

Centroid Frequency Down Shift (CFD) Method:

Centroid frequency down shift method (Quan and Harris,1997) calculates Q from the decrease in centroid frequency of a spectrum of seismic wave traveling through an lossy medium. The centroid frequency shift and variance of first arrival wavelet is used to calculate attenuation. The Q estimation of VSP data is done by the following equation.

$$Q_s = -\frac{\mu \sigma_s^2 \Delta t}{f_c} \tag{5}$$

Where the centroid frequency shift f_c is the difference between the source (f_s) and received signal (f_r) and σ^2_s variance of source signal.

Attenuation Estimation

We started to analyse the effect of attenuation with single layer model (Fig.4 to Fig.8). The reliable estimation of attenuation is easier for single layer model than for a multi-layered model. The linear plot of frequency-logarithmic spectral ratio of non-attenuative model is flat i.e. the slope of the linear plot has to be zero (Fig.5) where the value of Q is ∞. The amplitude spectra or energy of the seismic signal is reduced from 260 to 54 in the high attenuative media (Fig.7a) and 460 to 250 in the low attenuative media (Fig.8a) at depth level 90 to 190m. It is also noted that seismic signals are broadened with time. The amplitude spectra in high attenuative media is relatively narrow frequency band up to 120Hz which explains that the high frequencies are more vulnerable to attenuation than the low frequencies. The estimated Q by spectral ratio method for high and low attenuative media is 5.28 and 43.78 respectively. On the other hand Q estimated by centroid frequency downshift method is 5.09 and 47.32 respectively (Fig.10).

Multi-layering introduces reflection, refraction, and mode conversion of seismic energy and reduces the level of arrival energy. Three layered model experiment has been conducted to study the effect of high attenuative media within low attenuative media and vise versa (Fig.11 to 15). The result of Q estimation computed by both SR and CFD method is illustrated in the Fig. 15 with model Q values. Layer wise quality factor, Q of the first model (Fig.11c) is 8.11, 42.17 and 9.88, and 43.16, 8.04 and 51.15 for the second model (Fig. 13c) estimated by using SR method. On the other hand Q estimated by CFD method is 7.2, 55.12, and 8.71 for the first model and 50.32, 8.42 and 49.46 for the second model.

Conclusions

The reliable estimation of attenuation is much easier for a single layered isotropic model than for a multi-layered model because of its simple model configuration. Multi-layering adds transmission, reflection loss, mode conversion of wave that caused loss of energy from data and noise can be added to the data from any kind of sources other than seismic sources as to the VSP. So the accuracy of the attenuation estimation must be tested on different multi layered conditions. Moreover, the multi-layering introduced different order of multiples in the seismogram by trapping the reflected energy in between top and bottom interface of the layer. So the multi-layered model synthetic seismograms have noise content which is one of the main constraints in reliable attenuation estimation. In these model dependent experiments, it showed that the attenuation measurement techniques are more accurate in the simple models. Model complexity introduces reflection, transmission, scattering effect in seismogram that influence the Q computation. The Q estimation by spectral ratio method of closely spaced receiver pair is more erroneous than that of the receiver pair spaced comparatively larger depth; because the scattering effect tends to influence the amplitude spectra more. Our result suggests that it is reasonable to draw a conclusion about seismic attenuation at maximum frequency band width of 0-150Hz. The CFD method is more robust than SR method on this model based attenuation analysis. The overall estimated Q values of different models is high 50±6 and low 5±3 respectively. These results are support the Amundsen and Mittet Q bound of approximately 50. Despite of the uncertainty in wave field separation, widowing, first break time picking, selection of right frequency band width, and multiple suppression etc. the main conclusion drawn from this study is that it is feasible to estimate Q for layered media.

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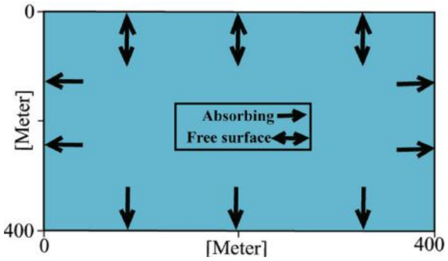

Fig. 1: Model boundary condition. The model space is made de up of unit cells in 2D space. The upper boundary is free surface and the both side walls and bottom interface having absorbing boundary condition.

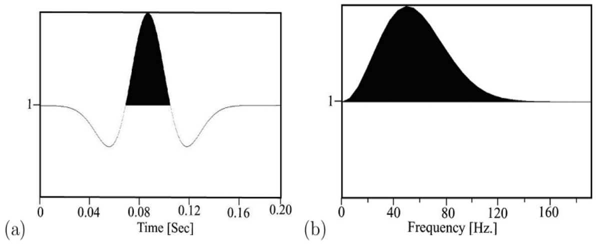

Fig. 2: Source function, single ricker wavelet with 50Hz dominant frequency is used in seismic modeling (a) in time domain (b) in frequency domain

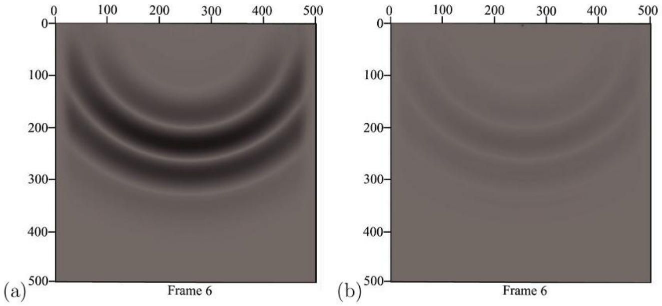

Fig. 3: A snapshot of movie frame of wavefield within the numerical model with V p=3500 m/s, ρ=2.60 gm/cm (a) non-attenuative media (b) attenua-tive media (Q=5)

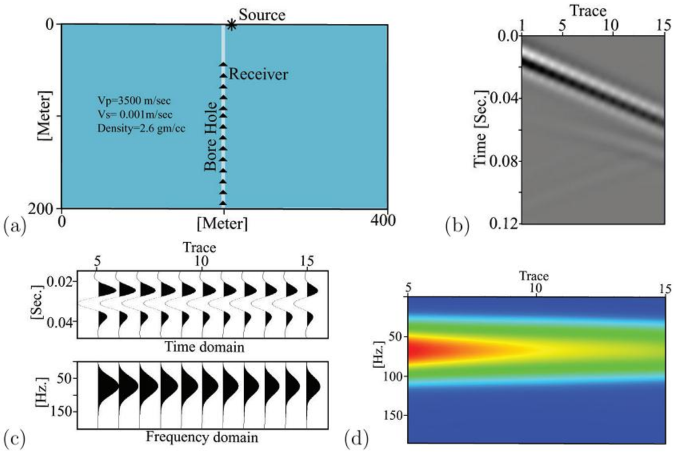

Fig. 4: Non-attenuative model (a) model and VSP source receiver geometry (b) total wavefield in time domain (c),(d) windowed downgoing direct wavefield in time and frequency domain.

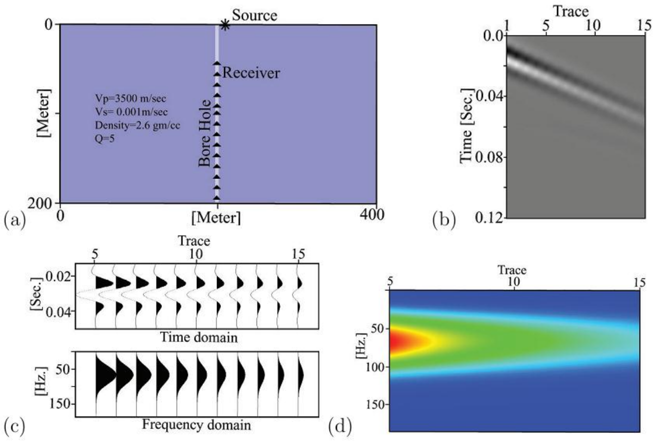

Fig. 6: Single layered high attenuation model (Q=5) (a) model and VSP source receiver geometry (b) total wavefield in time domain (c),(d) windowed downgoing direct wavefield in time and frequency domain.

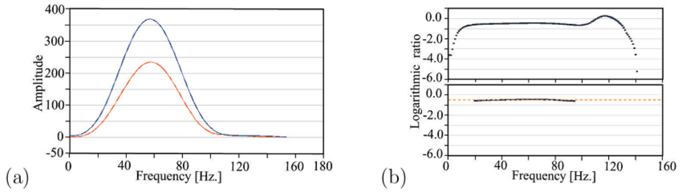

Fig. 5: Amplitude spectra and logarithmic spectral ratio of non-attenuative model shown in the Fig. 4 (a) traces recorded at 90m (blue) and 190m (red) depth (b) top: total frequency band width and bottom: 20-100Hz. frequency band width.

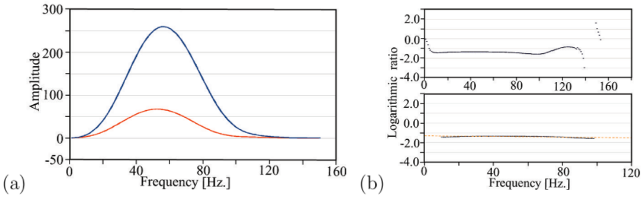

Fig. 7: Amplitude spectra and logarithmic pectral ratio of single layered high attenuation model shown in the Fig. 6 (a) traces recorded at 90m (blue) and 190m (red) depth (b) top: total frequency band width and bottom: 10-100Hz. frequency band width.

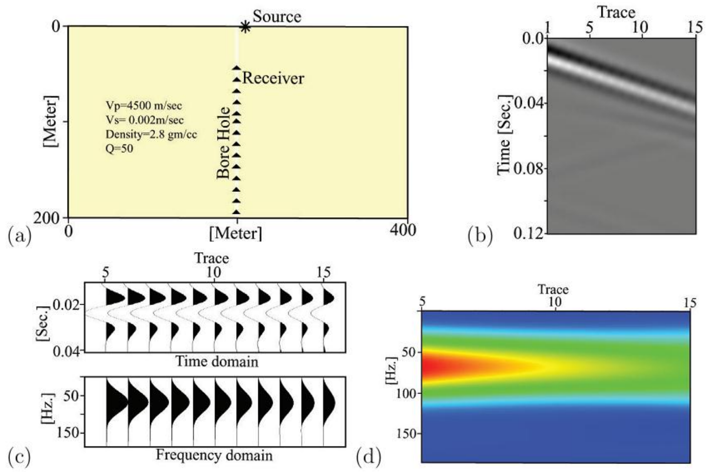

Fig. 8: Single layered low attenuation model (Q=50) (a) model and VSP source receiver geometry (b) total wavefield in time domain (c),(d) windowed downgoing direct wavefield in time and frequency domain.

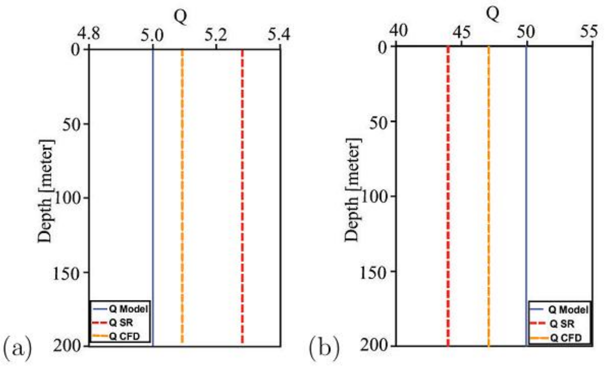

Fig.10: Q modeling result of single layered attenuation models where shows model value (blue line) and estimated values from SR method (red line) and CFD method (orange line) (a) high attenuation model (Q=5) shown in the Fig. 6a and (b) low attenuation model (Q=50) shown in the Fig. 8a

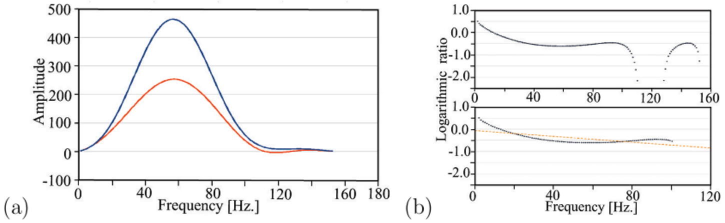

Fig. 9: Amplitude spectra and logarithmic spectral ratio of single layered low attenuation model shown in the Fig.8 (a) traces recorded at 90m (blue) and 190m (red) depth (b) top: total frequency band width and bottom: 0-100Hz. frequency band width

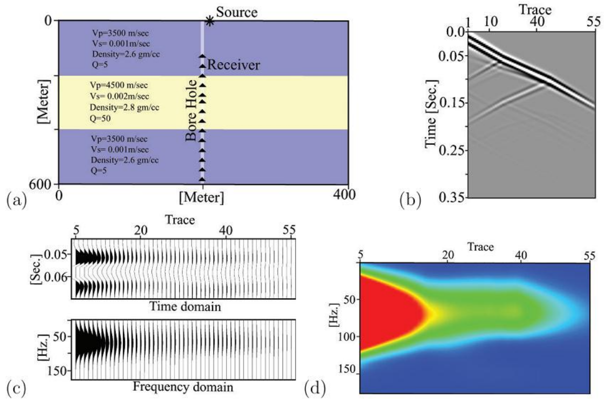

Fig. 11: Three layered attenuation model with first layer: high attenuation (Q=5), second layer: low attenuation (Q=50), and third layer: high attenuation (Q=5) (a) model and VSP source receiver geometry (b) total wavefield in time domain (c),(d) windowed downgoing direct wavefield in time and

frequency domain.

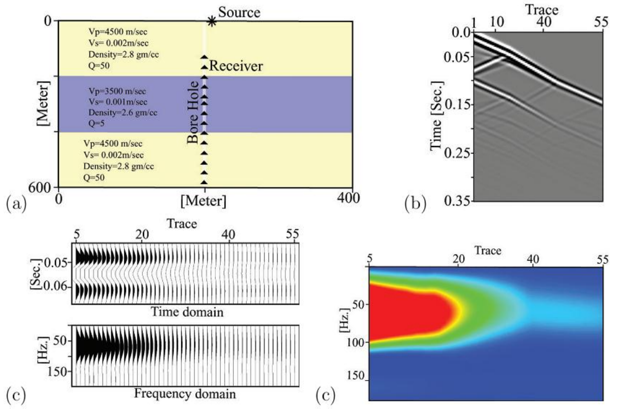

Fig. 13: Three layered attenuation model with first layer: low attenuation (Q=50), second layer: high attenuation (Q=5), and third layer: low attenuation (Q=50) (a) model and VSP source receiver geometry (b) total wavefield in time domain (c),(d) windowed downgoing direct wavefield in time and frequency domain.

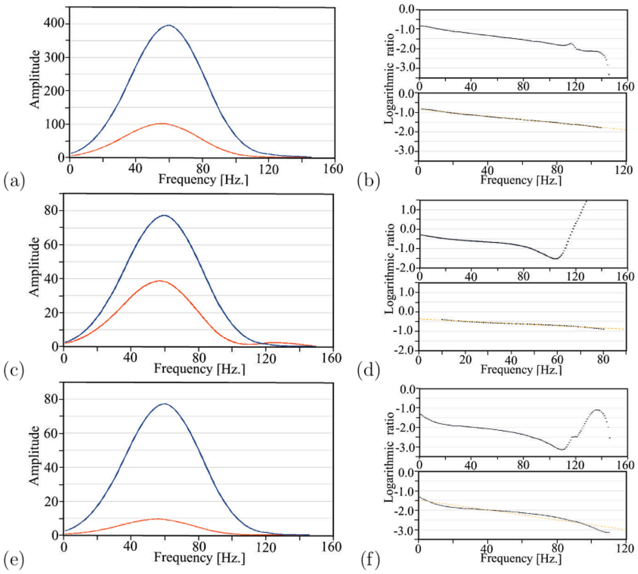

Fig. 12: Amplitude spectra [(a),(c),(e)] and logarithmic spectral ratio [(b),(d),(f)] of the three layered attenuative model shown in Fig. 11a (a) traces recorded at 90m (blue) and 190m (red) depth (b) logarithmic spectral ratio [Fig. 12a] top: total frequency band width and bottom: 0-100Hz. frequency band width (c) traces recorded at 210m (blue) and 390m (red) depth (d) logarithmic spectral ratio [Fig. 12c] top: total frequency band width and bottom: 10-80Hz. frequency band width (e) traces recorded at 410m (blue) and 590m (red) depth (f) logarithmic spectral ratio [Fig. 12e] top: total frequency band width and bottom: 0-110Hz. frequency band width.

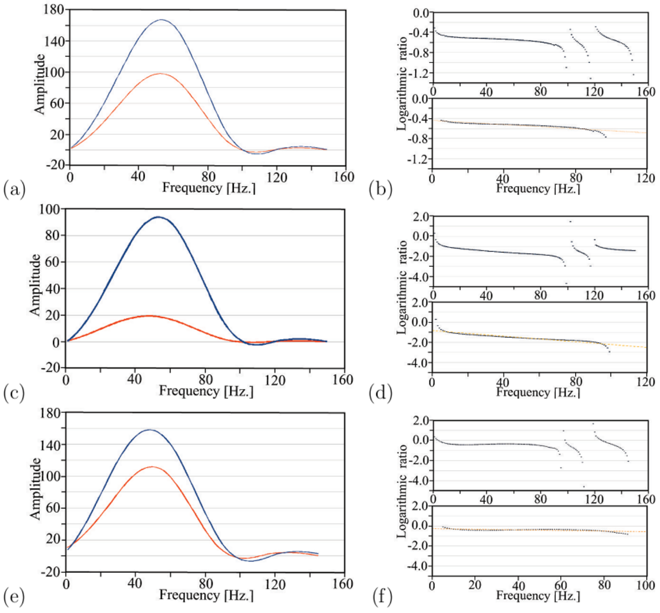

Fig. 14: Amplitude spectra [(a),(c),(e)] and logarithmic spectral ratio [(b),(d),(f)] of the three layered attenuative model shown in Fig. 13a (a) traces recorded at 90m (blue) and 190m (red) depth (b) logarithmic spectral ratio [Fig. 14a] top: total frequency band width and bottom: 5-90Hz. frequency band width (c) traces recorded at 210m (blue) and 390m (red) depth (d) logarithmic spectral ratio [Fig. 14c] top: total frequency band width and bottom: 0-100Hz. frequency band width (e) traces recorded at 410m (blue) and 590m (red) depth (f) logarithmic spectral ratio [Fig. 14e] top: total frequency band width and bottom: 5-90Hz. frequency band width.

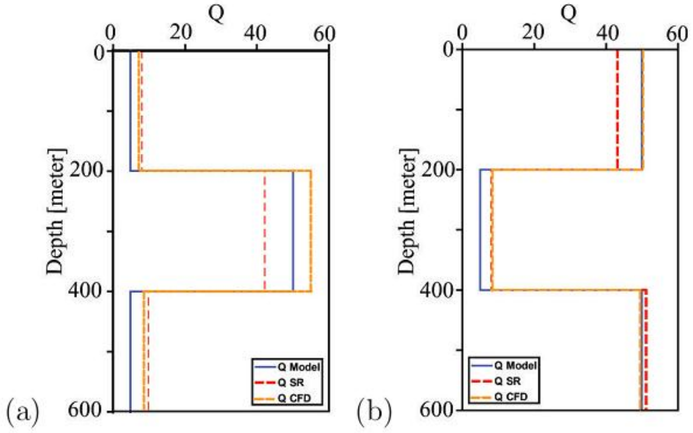

Fig. 15: Q modeling result of three layered attenuation models where model value (blue line) and estimated values from SR method (red line) and CFD method (orange line) for the attenuation model (a) as shown in the Fig. 11a and (b) attenuation model as shown in the Fig. 13a.