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Frequency-dependent near-surface *Q* factor measurements via a cross-hole survey

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ABSTRACT

We have measured near-surface absorption in a site of Daqing Oilfield, China, by using a cross-hole survey. The near-surface was divided into two layers according to the water table depth, the weathering and sub-weathering layers. The seismic attenuation for each layer was analysed in detail to estimate the quality factor *Q* and investigate its dependency on frequency. The absorption model was estimated using tomographic absorption inversion without source effect. The inverse *Q* factor for the weathering layer is much smaller than that for the sub-weathering layer, indicating that absorption decreases when the near-surface is saturated with water. The Q^{-1} factors for the two layers vary with frequency in a similar way, increasing with frequency at the low frequency end, reaching its maximum value at a characteristic frequency and then decreasing with increasing frequency. The results closely match theoretical predictions and laboratory measurements and therefore can be treated as reliable evidence of frequency-dependent *Q* factor.

1. Introduction

Seismic wave propagation through unconsolidated near-surface sediments suffers from strong absorption, which can be quantified by quality factor *Q*. The near surface absorption can be used to enhance seismic resolution by inverse filtering (Wang, 2006). Moreover, since the *Q* factor is directly related to the damping ratio of the material being studied, it can be used in earthquake engineering, geotechnical engineering, ground-water studies, environmental studies, and earthquake seismology (Xia et al., 2012). Schock (2004) and Pinson et al. (2008) have even used the estimated *Q* values to determine the mean grain size of unconsolidated marine sediments.

As yet, there is no consensus about the frequency dependence of *Q*. Although it is generally accepted that *Q* is independent of frequency (Lupinacci and Oliveira, 2015), results from theoretical studies on attenuation mechanisms and from laboratory measurements of core samples tend to suggest that *Q* can, in fact, depend on frequency (White, 1975; Johnston et al., 1979; Brajanovski et al., 2006; Pride et al., 2004).

A number of studies have been done about measurements of frequency-independent *Q* via the surface reflection seismic, vertical seismic profile (VSP), and cross-well seismic surveys. Hatherly (1986) used seismic refraction data to measure shallow absorption by examining the variation of seismic pulse width with distance. Badri and Mooney (1987) measured absorption in near-surface unconsolidated sediments and then estimated *Q* by three different methods, although the results were inconclusive. Brzostowski and McMechan (1992) performed tomographic imaging of near-surface absorption by using surface seismic data. Zhang and Ulrych (2002) derived an analytical relation between *Q* factor and seismic data peak frequency variation both along offset and vertical time direction, and estimated *Q* factor from CMP gathers using a layer-stripping approach. Yadari et al. (2008) inverted weathering layer absorption by using seismic wave propagation modelling. Reine et al. (2012) developed a robust method for measuring attenuation from prestack surface seismic gathers by making use of a variable-window time–frequency analysis.

In contrast, there have been few measurements of frequency-dependent *Q*. Kan et al. (1983) claimed to have observed frequency-dependent *Q* in a spectral analysis of vertical seismic profile (VSP) data, although their claim is controversial. Harris et al. (1997) also attempted to estimate frequency-dependent *Q* by using VSP data, although little evidence of frequency dependence was found. Jeng et al. (1999) reported an in situ measurement of frequency-dependent *Q* by using direct waves fired on the ground surface. Jones (1986) attributed the lack of in situ evidence for frequency-dependent *Q* both to the difficulty of making appropriate seismic measurements and to the narrow bandwidth of seismic data acquired in the field.

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We conducted a near-surface absorption measurement in Daqing Oilfield, China. The direct waves with high quality were acquired via a cross-hole survey. Their spectra and spectral ratios have been analysed in detail to investigate Q and its dependence on frequency. Based on the observed non-linear attenuation with frequency, frequency-dependent near-surface absorption has been estimated using tomographic inversion without source effect. The behaviour of the estimated Q closely matches theoretical predictions and laboratory measurements; therefore, this data can be considered as reliable evidence of frequency-dependent Q.

2. Theory and methods

2.1. Seismic absorption and its characterisation

Seismic absorption can be expressed as the quality factor Q. Knopoff and McDonald (1958) defined Q as the ratio of the maximum strain energy E_0 to the dissipation energy ΔE:

$$Q = 2\pi \frac{E_0}{\Delta E}. \tag{1}$$

Dissipation or absorption can be described by a linear relation between stress σ and strain ε with a complex viscoelastic modulus M:

$$\sigma = M\varepsilon. \tag{2}$$

The Q factor can also be defined as

$$Q = \frac{\mathrm{Re}(M)}{\mathrm{Im}(M)} = \frac{1}{\tan\varphi}, \tag{3}$$

where φ is the phase of the complex modulus (White, 1965).

Seismic wave propagation in a one-dimensional viscoelastic medium can be described by

$$\frac{\partial^2 u}{\partial t^2} = \frac{M}{\rho}\frac{\partial u^2}{\partial r^2}, \tag{4}$$

where t is time, ρ is density, and r is distance. The solution of Eq. (4) can be expressed as

$$u(r,t) = u_0 \exp[j(\omega t - kr)], \tag{5}$$

where j is the square root of -1, ω is angular frequency, and k is a complex wave number expressed as

$$k = k_r + jk_i = \frac{\omega}{v(\omega)} + j\frac{\pi f}{Q \cdot v(\omega)} \tag{6}$$

where v is velocity, and f is frequency. The real part of the equation represents velocity dispersion, which results in waveform distortion, while the imaginary part represents frequency-dependent energy attenuation.

2.2. Estimation of Q factor via spectral ratio analysis

Spectral ratio method (SRM) is widely used for estimating Q. According to Eq. (5), the amplitude spectrum of a seismic signal can be expressed as

$$u(r,f) = s(f)p(r)g(f)\exp\left(-\frac{\pi f r}{Qv}\right), \tag{7}$$

where v is velocity, $s(f)$ is the source signature, $g(f)$ is the geophone coupling response, and $p(r)$ accounts for geometrical spread and transmission loss and is assumed to be frequency independent. Taking the natural logarithm of the ratio of amplitude spectra at two distances, r_2 and r_1, we obtain

$$\ln\frac{u(r_2,f)}{u(r_1,f)} = \ln\frac{s_2(f)g_2(f)}{s_1(f)g_1(f)} + \ln\frac{p_2(r_2)}{p_1(r_1)} - \frac{\pi f(r_2 - r_1)}{Qv}. \tag{8}$$

If the source signature and the receiver coupling response are kept invariant, the above equation is simplified to

$$R(f) = a - \frac{\pi\Delta t}{Q} f, \tag{9}$$

where $\Delta t = (r_2 - r_1)/v$, a is a frequency-independent constant, $R(f) = \ln[u(r_1,f)/u(r_2,f)]$ is referred to as attenuation function. Assuming that Q is frequency independent in a certain frequency band, $R(f)$ is a linear function of frequency f with slope $p = -\pi\Delta t/Q$. Hence, the Q factor can be estimated from the slope p by

$$Q = -\frac{\pi\Delta t}{p}. \tag{10}$$

When Q is frequency dependent, the attenuation function $R(f)$ becomes nonlinear. In this case, the frequency dependent Q can be approximately estimated by piecewise linearly fitting.

In addition to SRM, there is a variety of other Q estimation methods. The basis of the risetime method is the dispersion of a travelling wavelet (Tonn, 1991), it estimates the Q factor by means of an empirical relation between attenuation and risetime (Gladwin and Stacey, 1974). The amplitude decay method estimates Q according to the amplitude decay with distance (Tonn, 1991), however, apart from the earth absorption, the amplitude decay is often affected by pure geometric factors such as geometric spreading. Hence, the geometric factors have to be removed prior to Q estimation. Instead of measuring amplitude decay, SRM estimates Q by measuring the evolution of frequency content, which makes it free of geometric effect. In this paper, we use the tomographic inversion, combined with SRM, to estimate the near surface absorption.

2.3. The uphole survey method and its limitations in estimating Q

The uphole survey technique is commonly used to investigate near-surface thickness and velocity for datum static correction. Sheriff (1991) defined an uphole survey as the use of successive sources at varying depths in a borehole to measure velocity in near-surface formations, to determine weathering thickness, and (sometimes) to analyse variations in seismic record quality according to source depth. Fig. 1 shows a simplified diagram of an uphole survey and its results. A borehole is drilled from the ground surface to a level which should be deep enough to sample all relevant near-surface layers, including the weathered layer and one or more sub-weathered layers. Sources are fired at various depths from deep to shallow, and the direct waves are recorded by geophones on the ground surface (Fig. 1a). Once the data have been acquired, the times from the source to the receiver are measured and adjusted with a geometric correction to generate vertical times. The adjusted and corrected times are then plotted on a time–depth display, the slope of which gives the interval velocity (Fig. 1b). There is another type of in-hole survey, sometimes called downhole survey, with the source at or close to the surface, and the receivers downhole. The downhole survey is less used in industry because of the difficulty and cost of fixing geophones securely on the borehole wall in the unconsolidated layer.

Since the VSP survey technique has already been widely used to estimate subsurface absorption (Hauge, 1981; Harris et al., 1997), it would seem that uphole surveys, as a small-scale VSP survey, could be naturally extended for use in estimating near-surface absorption. However, it usually fails because of source signature variation with depth. Source