Th-01-02

Q Estimation from Surface Waves

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SUMMARY

Despite the fact that surface waves in land seismic data are often regarded as noise, they can also be used to obtain valuable information about the subsurface. Because their propagation is directly related to the properties of the subsurface, the analysis and inversion of surface waves can provide a characterisation of the near surface.

In this paper, surface waves were used to estimate the dimensionless quality factor Q, which is most commonly used to measure the attenuation of seismic waves. To invert for the quality factor Q, the surface-wave attenuation coefficient and the phase velocity, as well as the near-surface S- and P-wave velocities, are needed. A weighted damped least-squares algorithm was chosen for the inversion. The algorithm produced promising results both for synthetic data, used to test different subsurface conditions (not shown here), and for real data sets, providing information about the subsurface that is not yet obtainable with other techniques.
Introduction

Surface waves are usually regarded as noise (Figure 1a and Figure 1b); however, these waves are not merely noise. They also contain valuable information, which can be used for velocity as well as geological modelling. Because the propagation properties of surface waves are directly related to the elastic properties of the near surface, a characterisation of the near surface can be provided by the analysis and inversion of surface waves (Strobbia et al. 2011). In dissipative media, the propagation of surface waves is also influenced by damping properties of the near surface, resulting in amplitude attenuation with offset (Figure 1c).

The dispersion, attenuation, and hence, amplitude spectra of surface waves are strictly related to the site properties and have been used to derive 1D S-wave velocity profiles and attenuation models for geotechnical applications (Lai et al. 2002; Foti 2004). The S-wave velocity is obtained by inverting the dispersion; whereas, the inversion of the attenuation results in an estimation of the quality factors $Q_S$ and, when it is possible, $Q_P$ (Xia et al. 2002).

Our objective is to estimate the quality factor $Q$ for P- and S-waves from surface waves contained in land seismic data. The desired result is a distribution of the quality factors $Q_P$ and $Q_S$ for the near surface of the acquisition area.

\[ A_1 = A_0 \times G(r_1 - r_0) \times e^{-\alpha_I(r_1 - r_0)} \times e^{-\alpha_A(r_1 - r_0)} \]

where $A_1$ and $A_0$ are the amplitudes at the distance $r_1$ and the source point $r_0$, respectively. The function $G(r_1 - r_0)$ represents the geometrical spreading, and $e^{-\alpha_I(r_1 - r_0)} \times e^{-\alpha_A(r_1 - r_0)}$ are the intrinsic and apparent attenuation with their respective attenuation coefficients $\alpha$. Apparent attenuation is caused by scattering, leakage or by abrupt lateral variations phenomena such as reflection, transmission, and others and it conserves energy. Intrinsic attenuation, on the other hand, is the irrecoverable loss or conversion of wave energy into heat and is a material property (Liner 2012).

Figure 1 a) An example of a shot gather showing strong surface waves; b) the surface wave component in a) and c) amplitude decay with offset for the event in b) at 6Hz and 8Hz.

Surface-wave attenuation

The common physical principle of different surface-wave characterization methods is related to the fact that their penetration depends on their wavelengths, which, in turn, is responsible for the geometric dispersion. Analysing surface-wave propagation, it is possible to observe that different frequencies have not just different phase velocity, but also different attenuation with offset (Figure 1c). Different phenomena are responsible for the surface-wave amplitude decay with increasing distance from the source. In general, a distinction can be made between the geometrical spreading and the attenuation of surface waves. Geometrical spreading is independent of frequency and only related to the distance the wave has travelled from the source; whereas, attenuation can be divided into two subcategories: intrinsic and apparent attenuation (Liner 2012). The amplitude decay of a propagating seismic wave is given by:

\[ A_1 = A_0 \times G(r_1 - r_0) \times e^{-\alpha_I(r_1 - r_0)} \times e^{-\alpha_A(r_1 - r_0)} \]
The intrinsic attenuation of seismic waves is also inherently related to the intrinsic dispersion. Without this relationship, all attenuation models would lack causality. Intrinsic dispersion is negligible for some applications because, even for highly attenuating media, the velocity variation as a function of frequency is very small (Ursin and Toverud 2002).

In the same way that surface-wave phase velocities can be used to determine S-wave velocity and layer thickness, the intrinsic attenuation coefficient $\alpha_i$ of surface waves can be used to drive an inversion aiming to provide an estimate of the quality factors $Q_P$ and $Q_S$. The frequency-dependent surface-wave attenuation $\alpha_i$ in a medium with $i$ layers is given by:

$$\alpha_i(f) = \frac{\pi f}{V_R(f)^2} \left[ \sum_{i=1}^{n} V_{P,i} \frac{\partial V_R(f)}{\partial V_{P,i}} * Q_{P,i}^{-1} + \sum_{i=1}^{n} V_{S,i} \frac{\partial V_R(f)}{\partial V_{S,i}} * Q_{S,i}^{-1} \right]$$  \hspace{1cm} (2)

where $V_P$, $V_S$, and $V_R$ are the P-, S-, and surface-wave velocities, respectively (Anderson et al. 1965).

The influence of the P-wave on the surface-wave attenuation, is sizeable in arid environments, but can be negligible for a ratio of $V_P/V_S >> 2$, which is a typical value for saturated soils (Foti 2004; Xia et al. 2002).

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Once the surface-wave phase velocities $V_R$ have been estimated following one of the well established approaches (e.g. Strobbia et al. 2011), the estimation of surface-wave attenuation coefficients is based on the analysis of the spatial decay of the amplitude as a function of the distance from the source. As we only consider the intrinsic attenuation $\alpha_i$, the amplitudes must be corrected to account for geometric attenuation $G$ and scattered events must be excluded from the analysis. Once the corrections have been applied, the spatial decay is governed by an exponential law (Figure 1c), with the exponent being proportional to the material attenuation, so that experimental data can be used to estimate $\alpha_i$ (Xia et al. 2002). Figure 2 shows an example of distribution of $V_R(f)$ and $\alpha_i(f)$ along a receiver line.

![Figure 2](image_url)

**Figure 2** a) Surface-wave phase velocity ($V_R$) distribution along a receiver line and, b) Attenuation coefficient ($\alpha_i$) distribution along the same receiver line.

The relation expressed by equation (2) can be used to implement an inversion for the quality factor $Q$. The fundamental linear inversion problem in this case is described by:

$$d = G \ast m$$  \hspace{1cm} (3)

where $m$ is the model vector consisting of the inverse of the quality factors $Q_S$ and $Q_P$, $d$ is the data vector containing the phase velocity $V_R(f)$ and the attenuation $\alpha_i(f)$ distributions (Figure 2), and $G$ is
After testing several inversion algorithms, we selected the weighted damped least-squares algorithm because it proved to be the most effective and stable in our first tests.

Example

The data set used to demonstrate the method was acquired using point receivers. The receiver line spans a distance of approximately 7.5 km. The distributions for the surface-wave phase velocity $V_R$ and the attenuation coefficient $\alpha_f$ for this data set are shown in Figure 2. The frequency range varies from approximately 5 to 20 Hz. Figure 3 shows the final inversion results for this data set given the P- and S-wave velocity of the near surface. $1/Q_P$ shows a more or less homogeneous distribution, with most values in the range between 0.022 and 0.026, which corresponds to $Q_P$ of 38 to 45. This distribution is interrupted by several small areas of low $Q$ values and high attenuation in the top layers. Some of these areas even extend to the lower part of the profile. The distribution of $1/Q_S$ is partially similar. Most $Q_S$ values range from 15 to 40. A layer of high $Q_S$ values in the upper part of the dataset is followed by several small areas of low $Q$ values with increasing depth. These areas correlate to a degree with the ones seen in the $1/Q_P$ distribution. The uncertainties for the resulting distributions of $1/Q_S$ and $1/Q_P$ are approximately 10% for most parts of the distributions.

Figure 3 Near-surface visco-elastic model obtained from phase velocities and attenuation coefficients in Figure 2.

Figure 4 shows the amplitude response of a 70-Hz Ricker wavelet to the $V_P$ and $1/Q_P$ distributions in Figure 3. In areas with small values for $1/Q_P$, the wavelet response differs less from the original wavelet due to the smaller attenuation; whereas, large values for $1/Q_P$ lead to a strong attenuation of the wavelet. Furthermore, there is a correlation between the wavelet response and the seismic section shown in Figure 4. The area enclosed by the black box corresponds to the strongly attenuated wavelet in the right part of the receiver line.

Conclusions

We showed a technique to estimate the distribution of the quality factor $Q$ for P- and S-waves from surface waves contained in seismic data. $Q_P$ and $Q_S$ can be obtained by using an inversion algorithm, which requires as input the velocity and intrinsic attenuation coefficient of the surface wave, and the velocities of the S- and P-waves. The results for the real data set are promising because the method shows a qualitative match of relative low $Q$ to relative weak seismic data, and that gives some
confidence that the procedure is producing reliable results. This method provides information about the near surface that is not yet obtainable with other techniques. As stated by Cavalca and Fletcher (2009) and El Yadari et al. (2008), there are several ways to make use of this distribution in consecutive data analysis. For example, it can be useful to compensate for attenuation effects caused by near-surface heterogeneities in surface-seismic data and leading to very weak reflected signals.

Figure 4 Amplitude response of a 70-Hz Ricker wavelet to the $V_p$ and $1/Q_p$ distributions in Figure 3 and the relative seismic section. The black box identifies the area with stronger shallow attenuation.

Acknowledgements

We thank WesternGeco for permission to publish this work and our colleagues Claudio Strobbia and Ralf Ferber for valuable discussions.

References