Journal of Applied Geophysics 103 (2014) 31–42

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Using all seismic arrivals in shallow seismic investigations

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ARTICLE INFO

Article history:
Received 5 August 2013
Accepted 16 December 2013
Available online 7 January 2014

Keywords:
Seismic reflection
SV waves
Multichannel analysis of surface wave
Seismic refraction tomography
Surface wave filter
Hydrogeophysics

ABSTRACT

Near surface seismic investigations are expensive and time-consuming. Moreover, seismic processing usually focuses on one particular type of wave and wastes much of the information contained in seismic records that could be used to make near surface seismic surveys more valuable and cost effective. A workflow is proposed herein that combines seismic refraction tomography, multichannel analysis of surface waves (MASW), and seismic reflection using P-waves and SV-waves, which takes advantage of P-wave first arrivals, Rayleigh waves, and P-wave and SV-wave reflections, respectively. The use of the proposed methodology is shown through three case studies carried out in the Outaouais region, Quebec, Canada, using a 24-channel seismograph, vertical geophones, and a sledgehammer. The results show that it is possible to acquire SV-reflections at sites where a strong velocity reversal is present at the surface using only vertical geophones. Under that condition, or more generally when two component geophones are used, the proposed workflow leads to two complementary stacked sections: 1) an SV-wave section that has a high resolution even at shallow depths but can lack coherency and 2) a P-wave section that has better coherency but is blind at shallow depths. Two velocity models are also produced: an SV-wave model that combines the results from MASW and SV-wave reflections and a P-wave model that combines the results from seismic refraction and P-wave reflections. The workflow uses the frequency variant linear move-out (FV-LMO) surface wave filter, which is much more efficient than band pass or f-k filters to process SV waves. The value of many near surface seismic surveys can thus be enhanced by processing all propagation modes, especially when SV-wave reflections are present due to their high resolution.

1. Introduction

Seismic energy propagates in the earth through different types of waves (P, SH, SV, Rayleigh, Love, Stoneley) that can undergo reflections, refractions, conversions from one type to another and diffractions (Aki and Richards, 2002). Conventional seismic investigations focus on a particular seismic arrival. For instance, one of the most popular seismic methods to map the depth to bedrock, the seismic refraction method, uses direct and refracted P-waves (Hagedoorn, 1959; Palmer, 1981). First arrivals can also be processed using tomographic inversion techniques that require far less input from the interpreter, can take into account velocity inversions and support one-direction shot spreads (Sheenan et al. 2005; White, 1989; Zang and Toksöz, 1998). In many cases, the geophones and shot spacings used for refraction tomography are similar to those used in seismic reflection surveys, with shots at every two or three geophone intervals (Lanz et al., 1998).

Seismic reflection surveys normally use only reflections from P-waves or SH waves. Recent work by Pugin et al. (2008, 2009) showed the power of using SV-wave reflections, which exhibit high resolution at very shallow depths, similar to SH reflections. Although three component geophones are recommended to successfully acquire SV-wave reflections in all terrain conditions, Pugin et al. (2013) found that their polarization is more vertical in soft clayey soils and horizontal when the medium is hard, such as a sand deposit or outcropping rock. This indicates that SV-wave reflections may be recorded with vertical geophones over soft soils at certain sites.

Rayleigh waves can be processed by multichannel analysis of surface waves (MASW). This method has proven to be a reliable technique to assess SV-wave velocities (Park et al., 1998; Xia et al., 2002, 2003) and, in certain cases, their quality factor (Lai et al., 2002; Xia et al., 2012). The spread configuration of the geophones and seismic shots used in a typical MASW survey is similar to common seismic reflection field geometries (Park et al., 2002b).

As it was previously mentioned, these methods use a similar geometry in the field and multiple propagation modes carrying useful information are usually generated and recorded. Moreover, the unwanted modes of propagation are often regarded as noise and much effort is spent removing them. Therefore, only a fraction of the available information in seismic gathers is used and processed. By obtaining more information out of the same dataset using a more complete signal processing approach, the seismic acquisition can become more valuable and cost efficient. A workflow is presented herein that integrates the processing techniques specific to MASW, seismic refraction tomography, P-wave seismic reflection and SV-wave seismic reflection. The objective is to obtain useful information from all the seismic arrivals.

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0926-9851/$ – see front matter
http://dx.doi.org/10.1016/j.jappgeo.2013.12.009

The workflow puts an emphasis on SV-wave reflections due to their higher resolution than P-wave reflections.

The use of this processing workflow is illustrated through three case studies. The first case illustrates the full workflow for a survey designed for the acquisition of SV reflections. The second case describes the application of a surface wave filter, the frequency variant linear move-out (FV-LMO) filter proposed by Park et al. (2002a) which is a logical extension of the proposed workflow. The third case shows how the workflow can help identify the presence or absence of SV-wave reflections. The conditions necessary to acquire SV-wave reflections using only vertical geophones are discussed first.

2. Acquisition of SV-waves

The most common way to record S-waves is by using cross-line horizontal geophones with a cross-line polarized source (Haines and Ellefsen, 2010; Hunter et al., 2002). Using that configuration, SH-waves can be generated and recorded. In contrast, vertically polarized shear waves can be generated with any conventional sources and can be recorded by inline vertical and horizontal geophones (Helbig and Mesdag, 1982).

The direction of polarization of SV reflections depends on the angle of incidence and the velocity distribution and usually varies with offset. For that reason, vertical and horizontal geophones are usually required. However, in some geological settings, a significant amount of SV-wave energy can be recorded with vertical geophones, even at short offsets. One such setting is the presence of a strong velocity inversion close to the surface (Fig. 1). According to Snell's law, an incoming ray is horizontally shifted if a high velocity layer lies on top of a much slower layer. In that case, the particle motion becomes mostly vertical. Such a situation is quite common in clay deposits that are affected by freeze-thaw and wetting-drying cycles, which cause over-consolidation of the surficial layer that significantly increases its shear wave velocity (Motazedian and Hunter, 2008). Another common case is a paved or gravel road constructed on soft soils; the pavement then acts as a high velocity layer. In such conditions, a significant amount of SV-wave energy can be recorded using only vertical geophones as shown in Section 6. However, careful planning and testing are required to use only vertical geophones to acquire SV-waves and two-component (2-C) geophones are preferable in all circumstances.

3. Processing workflow

The processing workflow that combines MASW, seismic refraction tomography and SV- and P-wave reflection inversion is shown in Fig. 2. The SV- and P-waves are processed separately. The starting point of both processing flows is the spatially referenced seismic data. For the SV-wave processing, MASW is first performed to build an S-wave velocity model. The dispersion curves produced during this analysis are used to filter the surface waves. The SV-wave reflections are then inverted to obtain a stacked section and a combined MASW/reflection velocity model. The P-wave processing begins by picking first breaks, which are used for seismic refraction tomography and for surface static corrections. The P-wave reflections are then processed using the tomographic velocity model as a first estimate for the stacking velocities. Similar to the SV-wave processing, a P-wave stacked section and a combined refraction/reflection velocity model are produced. This is a general methodology, and the specific procedures of each inversion method could vary. The details of the present study are given in Section 6.

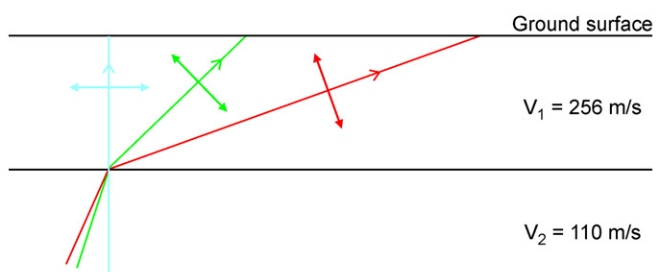

Fig. 1. Due to the presence of a strong velocity inversion close to the ground surface, the SV-waves particle motion is deflected to vertical. The velocities for this example are taken from a seismic piezocone penetration test (SCPTu) performed along the survey line of case study 1 (Fig. 3b) (Fabien-Ouellet et al., 2014).

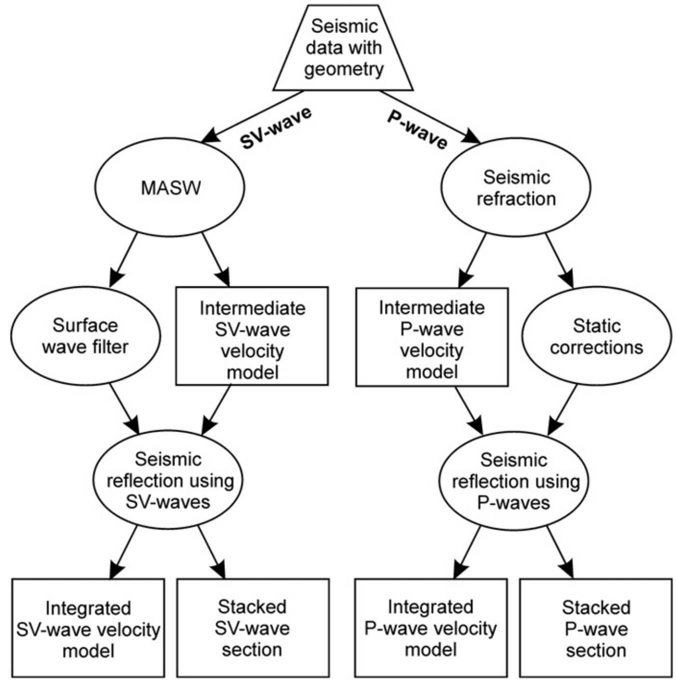

Fig. 2. Processing workflow combining MASW, SV-wave reflections, seismic refraction tomography, and P-wave reflections.

Even though 2-C geophones were not used in any of the case studies presented herein, this methodology is particularly well-suited for 2-C processing because all four seismic arrivals should be present in those records. In contrast, SV-wave reflection processing must be skipped for sites where SV-waves cannot be observed in the vertical component, but the rest of the workflow is still valid because surface waves and P-waves should usually be present.

4. The frequency variant linear move-out filter

It is critical to remove Rayleigh waves before performing the CMP inversion of the SV reflections. The velocities of P-waves and Rayleigh waves are so different that most of the surface wave energy is removed by CMP stacking. However, because Rayleigh waves travel at approximately 90% of the velocity of SV-waves, surface waves often overlap and even hide SV reflections. For this reason, performing the CMP inversion of SV reflections without previously removing surface waves can lead to spurious reflections on the stacked section.

Surface waves are normally removed using band-pass filters, f-k filters or muting. However, the frequency spectrums of surface waves and SV-waves often overlap and band-pass filters cannot effectively remove surface waves without removing a significant part of the desired signal. f-k filters are not well adapted for this filtering because the energy of surface waves is difficult to identify in the f-k domain. Moreover, the use of a simple velocity fan is problematic because of the multimodal and dispersive nature of surface waves. One of the most common techniques to remove surface waves is muting. However, muting can be subjective and a compromise must be made between removing surface waves and preserving SV reflections. It is often