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Acquisition and deconvolution of seismic signals by different methods to perform direct ground-force measurements

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ABSTRACT

We present the results of a novel borehole-seismic experiment in which we used different types of onshore—transient-impulsive and non-impulsive—surface sources together with direct ground-force recordings. The ground-force signals were obtained by baseplate load cells located beneath the sources, and by buried soil-stress sensors installed in the very shallow-subsurface together with accelerometers. The aim was to characterize the source's emission by its complex impedance, function of the near-field vibrations and soil stress components, and above all to obtain appropriate deconvolution operators to remove the signature of the sources in the far-field seismic signals. The data analysis shows the differences in the reference measurements utilized to deconvolve the source signature. As downgoing waves, we process the signals of vertical seismic profiles (VSP) recorded in the far-field approximation by an array of permanent geophones cemented at shallow-medium depth outside the casing of an instrumented well.

We obtain a significant improvement in the waveform of the radiated seismic-vibrator signals deconvolved by ground force, similar to that of the seismograms generated by the impulsive sources, and demonstrates that the results obtained by different sources present low values in their repeatability norm. The comparison evidences the potentiality of the *direct* ground-force measurement approach to effectively remove the far-field source signature in VSP onshore data, and to increase the performance of permanent acquisition installations for time-lapse application purposes.

1. Introduction

The accurate estimation of the source wavelet in signals emitted from seismic exploration sources is a goal of paramount importance for effective seismic-signature inversion purposes, in order to achieve the maximum permitted temporal resolution with the available data bandwidth and noise (Osman and Robinson, 1996). Similar considerations hold for controlled exploration and non-controlled seismic sources. A reliable source signature estimate would make it possible to improve surface-reflection and borehole data obtained by vibrator sources, using alternative reference deconvolution approach instead of conventional crosscorrelation (Brittle et al., 2001; Mewhort et al., 2002; Yudong et al., 2010). Besides resolution improvement, the ability to perform a robust source-signature removal or shaping by inversion is also potentially beneficial for time-lapse analysis purposes, which would require and benefit from improved source (as well as receiver) repeatability (Calvert, 2005).

We adopt the deterministic approach to measure the source signature in the near field, and utilize this signal for the processing of the far-field data. The conceptual motivation for adopting this method follows from the basic theory of radiating plates by a force source applied at the surface of a semi-space. This theory demonstrated the—at present well known—result that the wavelet signature of the signal radiated in the far-field is proportional to the time derivative of the applied force (Miller and Pursey, 1954). The relation between near-field and far-field waves of a point source was also theoretically investigated for the deconvolution of the wavelet from marine array sources by Ziolkowski (1980), and Ziolkowski et al. (1982). Sallas (1984) proposed a phase-control method of the force exerted by a seismic vibrator (ground force), together with a method to estimate the ground force by calculating the dynamic force F_g upon the earth's surface as proportional to the weighted sum of the accelerations of the vibrator baseplate mass (M_b) and the reaction mass (M_r), assumed as rigid bodies. This gives (Sallas, 1984)

$$-F_g = M_b\ddot{u}_b + M_r\ddot{u}_r, \tag{1}$$

where u is vertical displacement, the subscripts 'b' and 'r' denote baseplate and reaction mass, respectively, and the dot denotes time

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derivative. In this calculation he assumed negligible the vibration effects induced by the hold-down mass, and the base-plate flexural vibration modes. After Lerwhill (1981), Safar (1984) and Sallas (1984), Schrodt (1987) discussed techniques for improving Vibroseis data by adaptive closed-loop amplitude control of ground force, comparing phase-locking of ground force with far-field signals and base-plate and reaction mass acceleration, recommending phase locking to the ground force combined with ground force amplitude control. The wavefield in and at the surface of an homogeneous, isotropic, elastic half space was further investigated for the modeling of the vibroseis source by Baeten et al. (1988), with the derivation of the far-field relations. The analysis was extended to layered acoustic and elastic media by Baeten and Ziolkowski (1990). They analyzed the interaction of the vibrating source with the shallow surface, expressed by the complex radiation impedance of the coupled earth and vibrator system, including the modeling of baseplate deflection effects. Methods of observation of the ground force preserved in the near-surface propagation modes, ground roll, were also proposed to design optimum inverse filter to remove harmonic distortion frequencies (e.g., Pecholcs, 2006). More recently, important efforts have been made to develop and test hydro-mechanical models and the control technology of the vibrator system coupled to the ground, to improve at low and high frequencies the ground-force output and the performance of vibrator sources (Wei, 2009; 2010), to reduce non-linear effects typically introducing harmonics in the source spectra (Wei and Phillips, 2013b). These technical improvements are beneficial for seismic exploration industry.

In our study, we use direct ground-force measurements by a deterministic approach, which would theoretically enable us to properly remove the source effects by deconvolving the far-field data with the measured ground-force signal (Ziolkowski, 1991; Ziolkowski, discussion at the Vibroseis Workshop, Prague, 2008), with the target of improving the bandwidth and the quality of the data (Bagaini et al., 2009). The aim of this experimental work is to investigate the method of near-field source monitoring, to demonstrate that, under appropriate recording conditions, direct measurements of ground force can be effectively used to remove the source signature in the far-field radiated signals, and to verify that the approach can help to compensate bandwidth differences and significantly improve the processing of seismic signals from different sources. In this paper, we analyze borehole-surface results, and do not discuss potential industrial aspects related to intensive and extensive use of this technology with land surface exploration sources (e.g., Bagaini, 2007; Do and Bagaini, 2010). We rather extend the analysis to arbitrary ‘non-seismic’ sources, and consider the possible use of the ground-force measurement application for time-lapse purposes. We have to be conscious that this method would remove the source-related effects, but not all the time-lapse variations due to near-surface effects, such as seasonal and meteoric conditions which may alter the water column and the seismic properties of the shallower layers (e.g., Zabihi Naeini, 2012).

We present the results of a ground-force experiment performed in an instrumented well-test site (Piana di Toppo, North-East Italy) during 2011 (Poletto et al., 2011b), using dual field stress and acceleration sensors buried at shallow depth and a portable load-cell system (Shan et al., 2009). This test substantially used onshore dual sensors in the near field, to characterize the source emission, rather than in the far field to improve the processing of the on-land near-surface radiated fields by dual signals combination as discussed by Poletto et al. (2012). On-land acquisition tests using geophone and hydrophone sensors buried in the near surface at shallow depths where also utilized for permanent seismic monitoring by Bakulin et al. (2012), to improve the signal processing of seismic data acquired in desert areas where complex surface and near-surface geological conditions can compromise the seismic data quality and repeatability.

The well facility we utilized for the experiment is equipped with a permanent array of outside-casing 3C borehole geophones from 35 to 240 m depth utilized for surface-borehole experiments for seismic wavefield study (Poletto et al., 2011a). In this site, an assembly of surface and near-surface load-cell, stress and acceleration sensors was installed in a hole dug at a fixed position to monitor the vertical emission by surface seismic sources (Poletto et al., 2011b). In this experiment we used different sources, of non-impulsive, such as vibrators, and impulsive (dropping mass) type. The results of the test are compared for different configurations of sources and adopted processing solutions. The analysis of the data compares acceleration and stress soil motions in the near-subsurface, where the wavefield changes rapidly for near-field effects, and makes it possible to obtain very similar and repeatable results with different sources after source signature deconvolution. At the same time, the availability of the dual soil-stress and acceleration sensors allowed us to analyze the complex near-field impedance and to characterize the emission of the sources according to the literature results of Bycroft (1956) also reported by Cassand and Lavergne (1971).

2. Background theory

Before discussing ground-force measurements, we revisit some background basic equations. Assume radiated wavefields from a surface vibrating source (e.g., vertically pulsating plate) over a semi space, exposed to harmonic force (Cassand and Lavergne, 1971)

$$F = F_S e^{i\omega t}. \tag{2}$$

This formulation is similar to the original formulation of Miller and Pursey (1954), which does not include the detailed calculation of radiation by distributed stresses under the surface of the vibrating and deflecting plate (Baeten and Ziolkowski, 1990). In this representation, we use the approximation $F_S = \sigma_S A$, where σ and A are the stress and plate area, respectively, and the subscript 'S' denotes source.

Neglecting the time dependence, the particle velocity wavefield v can be expressed in relation to the stress wavefield as

$$v = Y\sigma, \tag{3}$$

where

$$Y = Y_1 + iY_2 \tag{4}$$

is the complex radiation admittance, reciprocal of the complex radiation impedance Z, by definition

$$Y = \frac{1}{Z}, \tag{5}$$

and $i = \sqrt{-1}$. We may observe that using the admittance is equivalent to use the impedance, and in the following we use admittance for convenience of representation. We rewrite Eq. (3) as

$$v = (Y_1 + iY_2)\sigma. \tag{6}$$

Complex Y (and Z) include near- and far-field terms. Let r be the radial distance and $k = \omega/c$ the wavenumber, where $\omega = 2\pi f$ is the angular frequency, f is the frequency, and c the wave propagation speed in the medium. The near- and far-field regions can be defined by the radial distance

$$r = \frac{1}{k} = \frac{\lambda}{2\pi}, \tag{7}$$