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ScienceDirect
Comput. Methods Appl. Mech. Engrg. 296 (2015) 39–72
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Full-waveform inversion in three-dimensional PML-truncated elastic media

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Received 24 November 2014; received in revised form 6 July 2015; accepted 9 July 2015
Available online 30 July 2015

Abstract

We are concerned with high-fidelity subsurface imaging of the soil, which commonly arises in geotechnical site characterization and geophysical explorations. Specifically, we attempt to image the spatial distribution of the Lamé parameters in semi-infinite, three-dimensional, arbitrarily heterogeneous formations, using surficial measurements of the soil's response to probing elastic waves. We use the complete waveform response of the medium to drive the inverse problem, by using a partial-differential-equation (PDE)-constrained optimization approach, directly in the time-domain, to minimize the misfit between the observed response of the medium at select measurement locations, and a computed response corresponding to a trial distribution of the Lamé parameters. We discuss strategies that lend algorithmic robustness to our proposed inversion scheme. To limit the computational domain to the size of interest, we employ perfectly-matched-layers (PMLs).

In order to resolve the forward problem, we use a recently developed hybrid finite element approach, where a displacement–stress formulation for the PML is coupled to a standard displacement-only formulation for the interior domain, thus leading to a computationally cost-efficient scheme. Time-integration is accomplished by using an explicit Runge–Kutta scheme, which is well-suited for large-scale problems on parallel computers.

We verify the accuracy of the material gradients obtained via our proposed scheme, and report numerical results demonstrating successful reconstruction of the two Lamé parameters for both smooth and sharp profiles.
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Keywords: Full-waveform inversion; Seismic inversion; Inverse medium problem; PDE-constrained optimization; Elastic wave propagation; Perfectly-matched-layer (PML)

1. Introduction

Seismic inversion refers to the process of identification of material properties in geological formations [1–3]. The problem arises predominantly in exploration geophysics [4–7] and geotechnical site characterization [8]; it belongs

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http://dx.doi.org/10.1016/j.cma.2015.07.008
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to the broader class of inverse medium problems: waves, whether of acoustic, elastic, or electromagnetic nature, are used to interrogate a medium, and the medium's response to the probing is subsequently used to image the spatial distribution of properties (e.g., Lamé parameters, or wave velocities) [9–11]. Mathematically, algorithmically, and computationally, inverse medium problems are challenging, especially, when no *a priori* constraining assumption is made on the spatial variability of the medium's properties. The challenges are further compounded when the underlying physics is time-dependent, and involves more than a single distributed parameter to be inverted for, as in seismic inversion.

Due to the complexity of the inverse problem at hand, most techniques to date rely on simplifying assumptions, aiming at rendering a solution to the problem more tractable. These assumptions can be divided into five categories: (a) assumptions regarding the dimensionality of the problem, whereby the original problem is reduced to a two-dimensional [12,13,8,14], or a one-dimensional problem [15]; (b) assuming that the dominant portion of the wave energy on the ground surface is transported through Rayleigh waves, and thus, disregarding other wave types, such as compressional and shear waves, as is the case in the Spectral-Analysis-of-Surface-Waves (SASW) and its variants (MASW) [16]; (c) inverting for only one parameter, as is done in [17–20], where inversion was attempted only for the shear wave velocity, assuming the compressional wave velocity (or an equivalent counterpart) is known; (d) assumptions concerning the truncation boundaries, which are oftentimes, grossly simplified due to the complexity associated with the rigorous treatment of these boundaries [21]; and (e) idealizing the soil as a lossless medium, thus neglecting its attenuative properties; exceptions, which account for material attenuation, albeit in a simplified setting include the works in [22,23]. Over the past decade, continued advances in both algorithms and computer architectures have allowed the gradual removal of the limitations of existing methodologies. However, a robust methodology, especially for the time-dependent elastic case remains, by and large, elusive.

Among the recent works on inversion, which are similar to ours, we refer to Pratt et al. [24] who considered two-dimensional acoustic inversion in the frequency domain, and Epanomeritakis et al. [18] where full-waveform inversion was attempted for three-dimensional time-domain elastodynamics with a simple dashpot for domain truncation, but results were shown only for a single-parameter inversion. Kang and Kallivokas [11] considered the problem for the two-dimensional time-domain acoustic case, and used PMLs to accurately account for domain truncation. Kucukcoban [14] extended the work of Kang and Kallivokas to two-dimensional elastodynamics, and reported successful reconstruction of the two Lamé parameters for models involving synthetic data. Bramwell [25] used a discontinuous Petrov–Galerkin (DPG) method in the frequency domain, endowed with PMLs, for seismic tomography problems, advocating the DPG scheme over conventional continuous Galerkin methods, since it results in less numerical pollution.

In this paper, we discuss a systematic framework for the numerical resolution of the inverse medium problem, directly in the time-domain, in the context of geotechnical site characterization. The goal is to image the arbitrarily heterogeneous material profile of a probed soil medium, using complete waveforms[1] of its response to interrogating elastic waves, originating from the ground surface. To this end, the response of the soil medium to active sources (Vibroseis equipment) is collected by receivers (geophones) dispersed over the formation's surface, as shown in Fig. 1(a). Arriving at a material profile is then accomplished by minimizing the difference between the collected response at receiver locations, and a computed response corresponding to a trial distribution of the material parameters. Imaging near-surface deposits brings additional difficulties, typically not encountered in exploration geophysics. In geophysical explorations, the probing is over large length scales; thus, an accurate domain termination tool may not play a critical role. However, in geotechnical site characterization, one, typically, deals with a much smaller domain. Moreover, obtaining a high-fidelity image of the near-surface deposits has practical significance for the safe founding of infrastructure components; thus, having accurate termination conditions becomes critical. In this vein, and in the presence of heterogeneity, using PMLs for domain termination is the best available option, and is thus used in this work. The PML is a buffer zone that surrounds the domain of interest, and enforces the decay of outgoing waves. Fig. 1(b) shows a computational model, obtained through the introduction of PMLs at the truncation boundaries.

In order to address all the difficulties outlined earlier, we integrate recent advances in several areas. Specifically, we use (a) a recently developed state-of-the-art parallel wave simulation tool for domains terminated by PMLs, which renders the computational model associated with the near surface geotechnical investigations finite [26]; (b) a partial-differential-equation (PDE)-constrained optimization framework through which the minimization of the difference

[1] Using the complete waveform (complete recorded response) results in a full-waveform inversion approach.

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