Journal of Applied Geophysics 135 (2016) 43–54

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

Impact of density information on Rayleigh surface wave inversion results

Julian Ivanov [a,*], Georgios Tsoflias [b], Richard D. Miller [a], Shelby Peterie [a], Sarah Morton [a], Jianghai Xia [c]

[a] Kansas Geological Survey, 1930 Constant Ave, Lawrence, KS, United States
[b] Department of Geology, The University of Kansas, Lawrence, KS, United States
[c] School of Earth Sciences Zhejiang University 38 Zheda Road, Hangzhou, Zhejiang 310027 China

ARTICLE INFO

Article history:
Received 14 March 2015
Received in revised form 25 August 2016
Accepted 6 September 2016
Available online 9 September 2016

Keywords:
Rayleigh surface wave
Surface-wave inversion
Density
Density sensitivity
Shear-wave velocity
V_s

ABSTRACT

We assessed the impact of density on the estimation of inverted shear-wave velocity (V_s) using the multi-channel analysis of surface waves (MASW) method. We considered the forward modeling theory, evaluated model sensitivity, and tested the effect of density information on the inversion of seismic data acquired in the Arctic. Theoretical review, numerical modeling and inversion of modeled and real data indicated that the density ratios between layers, not the actual density values, impact the determination of surface-wave phase velocities. Application on real data compared surface-wave inversion results using: a) constant density, the most common approach in practice, b) indirect density estimates derived from refraction compressional-wave velocity observations, and c) from direct density measurements in a borehole. The use of indirect density estimates reduced the final shear-wave velocity (V_s) results typically by 6–7% and the use of densities from a borehole reduced the final V_s estimates by 10–11% compared to those from assumed constant density. In addition to the improved absolute V_s accuracy, the resulting overall V_s changes were unevenly distributed laterally when viewed on a 2-D section leading to an overall V_s model structure that was more representative of the subsurface environment. It was observed that the use of constant density instead of increasing density with depth not only can lead to V_s overestimation but it can also create inaccurate model structures, such as a low-velocity layer. Thus, optimal V_s estimations can be best achieved using field estimates of subsurface density ratios.

1. Introduction

Estimation of shear-wave velocity (V_s) is important for the evaluation of the stiffness properties of the near-surface materials; V_s increases as material shear strength (rigidity) increases. The multichannel-analysis of surface-wave (MASW) method was developed to estimate near-surface S-wave velocity from high-frequency (≥2 Hz) Rayleigh-wave data (Miller et al., 1999; Park et al., 1999; Xia et al., 1999). Shear-wave velocities estimated using MASW have been reliably and consistently correlated with shallow-well data. Using the MASW method, Xia et al. (2000) noninvasively measured V_s within 15% of downhole measurements in wells located along the seismic profile. As confirmed by numerous borings, Miller et al. (1999) mapped limestone bedrock with 0.3-m accuracy at overburden depths of about 4.5–9 m. Similar successful results have been reported in the literature, e.g. Ismail and Anderson (2007), including good agreement between surface-wave estimated V_s for the upper 30 m (a.k.a. V_s30) and invasive-methods (Moss, 2008; Comina et al., 2011). Anbazhagan and Sitharam (2008) estimated a relationship between MASW V_s and standard penetration test (SPT) N values that correlates well with the Japan Road Association equations. The MASW method has been used to characterize pavements (Ryden and Park, 2004), investigate sea-bottom sediment stiffness (Kaufmann et al., 2005; Park et al., 2005), map fault zones (Ivanov et al., 2006a), study Arctic ice sheets (Tsoflias et al., 2008) and subglacial sediments (Tsuji et al., 2012), obtain 3D V_s estimations in 3D reflection data (Strobbia et al., 2011), and map build up stress above voids (Ivanov et al., 2013). Studies using the MASW method have evaluated approaches for determining quality factor (Q) of the near-surface (Xia et al., 2002), and constraining seismic refraction inversion models (Ivanov et al., 2006b; Dal Moro et al., 2007; Ivanov et al., 2010; Socco et al., 2010a; Piatti et al., 2013). A review of established approaches of surface wave methods (SWM) can be found in Socco et al. (2010b).

The MASW method requires several unique steps (Miller et al., 1999). First, a single seismic-data record is acquired using a line of equally spaced (usually, for convenience) low-frequency (e.g., 4.5 Hz) vertical geophones. The seismic wavefield from such a shot record is transformed into a phase-velocity–frequency domain image (i.e., dispersion-curve image) (Park et al., 1998). This image is used to evaluate the dispersion-curve characteristics of the fundamental-mode Rayleigh wave. Next, the estimated dispersion curve is inverted (Xia et al., 1999) to produce a 1-D V_s model of the subsurface. This 1-D V_s function is assigned to a point in the middle of the geophone line

* Corresponding author.
E-mail addresses: jivanov@kgs.ku.edu (J. Ivanov), jhxia@zju.edu.cn, jianghai_xia@yahoo.com (J. Xia).

http://dx.doi.org/10.1016/j.jappgeo.2016.09.011

(a.k.a., spread). A pseudo-2-D V_s model is then built by assembling numerous 1-D V_s models each derived from seismic shot gathers recorded after each incremental advancement of shot and receiver locations (a.k.a., roll).

Most recent developments of the SWM include the definition of a suitable spatial window (e.g., MOPA method) to control near-field effect and lateral variations (Strobbia and Foti, 2006) and one based on wavelengths (Lu, 2015), the use of lateral constraints (Boiero and Socco, 2010), and space-varying special windowing (Bergamo et al., 2012) to handle 2-D effects. Recent research also includes the expansion with the use of the horizontal component of the Rayleigh wave (Boaga et al., 2013) and the Love-waves (Dal Moro et al., 2015), evaluation at landfill sites (Suto, 2013), understanding fault geometry (Ikeda et al., 2013), development of V_s profiles to depths of 100 m or deeper for earthquake-response microzonation (Murvosh et al., 2013), and the simultaneous use of guided-waves with multi-mode surface waves in land and shallow marine environments (Boiero et al., 2013).

MASW dispersion-curve inversion for V_s is commonly performed using predefined values for compressional-wave velocity (V_p) and density. It is preferred that such a-priori information is available from other measurements. However, practical MASW applications often lack this information and as a result the V_p and density estimates are determined based on assumptions for each specific site. It has been postulated that the resulting error from using parameter assumptions is insignificant. Xia et al. (1999) showed that a 25% increase in V_p resulted in less than 3% average change in the dispersion-curve phase-velocity values from forward modeling. Furthermore, forward modeling showed that decreasing the density in the top 2 layers by 25% and increasing it in the rest of the layers by 25% resulted in average V_s change of less than 10%.

In this study, we expand the above work reviewing the numerical surface-wave formulations and applying three types of model sensitivity studies to better understand the impact of density change within a single layer, a single density contrast change within a layered section, and overall density trend ratios. We also experimentally evaluated the effect of density information on the estimation of V_s. We employed the MASW method in the Arctic over snow and ice where density and V_s were well constrained, compared to typical near-surface geologic environments. Using constant density as a function of depth resulted in unrealistic V_s estimates and velocity inversion structures that were unlikely in an environment dominated by gradual compaction and densification of snow with depth. We observed the most realistic V_s estimates when we employed a density profile measured at a nearby ice-core.

2. Background

2.1. Theoretical background

The impact of density on surface wave inversion can be investigated by examining any of the numerical algorithms for Rayleigh-wave dispersion-curve estimation. Knopoff's method (Schwab and Knopoff, 1972), which is an improved version of the Thomson–Haskell technique (Thomson, 1950; Haskell, 1953) can be used for a layered earth model (Xia et al., 1999). This transfer matrix method is a preferred algorithm because of its simplicity and ease of computer implementation (Foti et al., 2015). However, other approaches, such as the dynamic stiffness matrix method (Kausel and Roesset, 1981) or the reflection and transmission coefficients method (Kennett and Kerry, 1979) can also be used. For brevity we list only a few parts of the implementations outlined by Schwab and Knopoff (1972) required to demonstrate the impact of density on the forward modeling computations (i.e., formulas are incomplete).

The Rayleigh-wave dispersion curve calculation function $F_R(\omega, c)$ can be written as:

$$F_R(\omega, c) = T^{(0)}\overline{F}^{(1)}F^{(2)}\overline{F}^{(e)} \cdots F^{(n-2)}\overline{F}^{(n-1)}T^{(n)}_{solid} \quad (1)$$

if n is even (when n is odd the formula is similar), where n is the total number of layers and $T^{(0)}$ and $F^{(m)}$ are matrixes and m is layer number.

The $T^{(0)}$ component (not shown for brevity) in Eq. (1) contains the density of the first layer, only (i.e., ρ_1). The $F^{(m)}$ matrix elements contain variables that include density only in the form of ratios in various relationships, e.g.:

$$\begin{array}{ll}
\varepsilon_0^{(m)} = \rho_{m+1}/\rho_m & \varepsilon_7 = \varepsilon_1\varepsilon_3 \\
\ldots & \varepsilon_8^{(m)} = \varepsilon_1^{(m)}\varepsilon_4^{(m)} \\
\varepsilon_2 = \varepsilon_1 - 1 & \varepsilon_{10} = \varepsilon_2\varepsilon_3 \\
\varepsilon_3 = \varepsilon_1 + \varepsilon_0 & \varepsilon_{11} = \varepsilon_2\varepsilon_4 \\
\varepsilon_4 = \varepsilon_2 + \varepsilon_0 &
\end{array} \quad (2)$$

It can be noticed in Eq. (2) that density ratios can be observed in the expression of $\varepsilon_0^{(m)}$, which is part of the expressions for ε_2,ε_3, and ε_4 which in turn are components of the expressions for other $\boldsymbol{\varepsilon}$ values. In these numerous interdependent expressions it is difficult to observe direct relationships and/or dependencies between variables. However, it can be noticed that in all expressions densities are presented in pairs and as ratios, i.e., their absolute values appear irrelevant to the computation process, and it is their ratios that affect the computations.

2.2. Previous sensitivity analysis

Xia et al. (1999) used a 6-layer model (Table 1) to calculate surface-wave dispersion curves, observe their changes due to changes in the model parameters, such as density, V_s, V_p, and thickness, and concluded that V_s. is the dominant parameter influencing the Rayleigh-wave velocity. Furthermore, they measured V_s inversion errors when using inaccurate V_p and density values up to 25%, separately and in combination, and reported 8% V_s deviation from the true model with as much as 23% for some layers. In order to maximize the effects of density variability on the dispersion curve, the first and second layers were decreased by 25% and the rest of the layers were increased by 25%. The resulting average relative change in phase velocity between the calculated dispersion curves before and after density changes were estimated to be <10% (Xia et al., 1999).

3. Methods and results

3.1. Model sensitivity analysis

3.1.1. Absolute density value changes

In this study the 6-layered model (Table 1) proposed by Xia et al. (1999) was used for a broader density sensitivity assessment. Fig. 1 shows calculated dispersion curve values for the fundamental mode and the next five higher modes of the Rayleigh wave for the original 6-layered model. To test the proposition that the absolute density-value changes do not affect the dispersion-curve estimations we used densities 75% from their original values for all the layers to again calculate the fundamental-mode and the first five higher modes of the Rayleigh wave (Fig. 1). All calculated dispersion-curves before density changes were identical to those from the model after all densities were reduced to 75%. For simplicity, further density sensitivity analysis will focus on the fundamental-mode, only.

Table 1
Six-layer model used by Xia et al. (1999).

Layer	Depth (m)	Thickness (m)	V_s (m/s)	V_p (m/s)	Density (g/cm^3)
1	2	2	194	650	1.82
2	4.3	2.3	270	750	1.86
3	6.8	2.5	367	1400	1.91
4	9.6	2.8	485	1800	1.96
5	12.8	3.2	603	2150	2.02
6	HalfSpace	N/A	740	2800	2.09