P- and S-wave velocity model estimation from surface wave data

Laura Valentina Socco
Politecnico di Torino

***Abstract*—Surface wave analysis performed on data acquired on purpose or extracted from seismic gathers acquired for body wave surveying is a powerful tool for S-wave velocity model estimation. S-wave velocity is relevant for many engineering applications, but the recent application for hydrocarbon exploration data processing (static corrections) makes the estimation of P-wave velocity a desired additional target of the method. Several approaches ranging from joint inversion to approximated direct estimation have been implemented in recent here and are here reviewed. These approaches, applied here on synthetic 1D examples have been also extended to 2D real world applications.**

Keywords—P-save; S-wave;velocity model estimation; surface wave data

I. INTRODUCTION

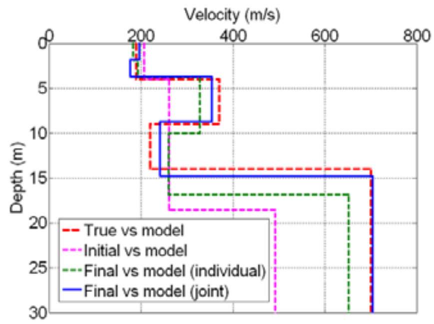
The analysis of the dispersion of surface waves has gained a great popularity in the last two decades. After the pioneer works of Park et al. (1999) and Xia et al. (1999) many methodological advances have been developed and the method is nowadays widely applied in a variety of exploration problems[1-3].

The inversion of the dispersion curve provides a 1D local velocity model. In spite Poisson's ratios (or P-wave velocity) of the layers are required model parameters for the forward mapping, previous studies[4] have shown that the sensitivity toward this parameter is very low. Hence, Poisson's ratio is usually assumed in the initial model and kept fix during the inversion, in which only S-wave velocity and layer thicknesses are considered unknown. The choice of Poisson's ratio values has nevertheless to be carefully performed, particularly in those cases in which an abrupt variation of Poisson's ratio occurs, for instance in correspondence of the water table[5].

In this context, surface wave analysis is recognized as a powerful tool to retrieve S-wave near surface velocity models [6-8], nevertheless, for seismic reflection processing, the P-wave velocity distribution in the weathering layer represents the most relevant information. Several approaches have been proposed to obtain P-wave velocity from surface wave analysis. Boiero et al. (2013), used information from borehole where the ratio between P- and S-wave velocity was available and transformed the S-wave velocity section obtained through surface wave analysis into a P-wave velocity section[9].

Several authors proposed to perform joint inversion of surface wave and body waves to exploit the different sensitivity patterns of the two methods and provide a reliable P- and S-wave velocity models both for individual velocity profiles. Recently, Socco and Comina (2015) and Socco et al. (2016), proposed an approximated but direct method to estimate S- and P-wave time average velocity profiles based on the relationship between investigation depth and wavelength of the dispersion curves. The time average velocity provides directly the value of one-way-time required for static corrections[10-11].

In the following the three aforementioned approaches are briefly outlined through1D synthetic examples and the extension to 2D data are explained.



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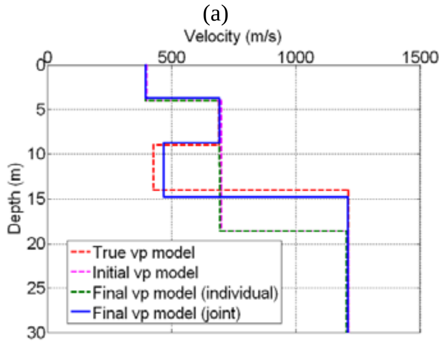

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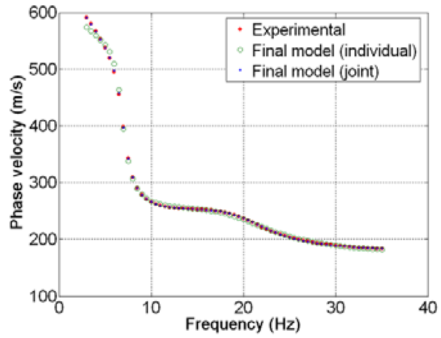

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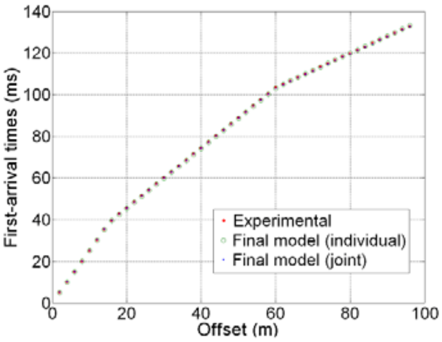

(d)

Fig.1 1D synthetic velocity model: comparison between individual and joint inversion of surface wave dispersion curves and P-wave travel times: a) inverted S-wave velocity models (individual and joint) compared with initial and true model; b) inverted P-wave velocity models (individual and joint) compared with initial and true model; c) fitting of synthetic dispersion curve at last iteration (individual and joint); d) fitting of the P-wave travel times at last iteration (individual and joint).

II. Joint Inversion of Surface and Body Waves

This approach does not relies on surface wave dispersion curves for the estimate of P-wave velocity but uses the structural information contained in the dispersion curve as a constraint to improve the estimate of P-wave velocity models from refracted P-wave travel time. Dal Moro (2008) performed a joint inversion using a bi-objective evolutionary algorithm in which the two seismic velocity models are coupled through Poisson's ratio[12]. Kis et al. (1995) jointly inverted geoelectric, refraction and seismic surface-wave data[13]. Forbriger (2003) applied the joint inversion of the complex Fourier-Bessel expansion coefficient of the recorded wavefield together with P-wave[14]. All these authors showed that joint inversion provides better results with respect to individual inversions allowing intrinsic ambiguities and equivalences to be mitigated, particularly for P-wave refraction data in the case of low velocity layers embedded in stiffer layers.

The example reported in Fig.1 refers to a joint inversion algorithm proposed by Patti et al. (2013), where P- and S-wave velocity models are constrained by imposing limits to Poisson's ratio values[15]. Several applications on synthetic and field data showed the improvement introduced by the joint inversion with respect to individual inversion.

The extension to 2D/3D dataset was proposed by Re et al. (2010); Glushchenko et al. (2012); and Boiero and Socco (2014) and successfully applied to hydrocarbon and engineering exploration datasets[1-18].

III. Inversion of Higher and Leaking Modes

Some authors have shown that higher modes are more sensitive to P-wave velocity than fundamental mode of propagation only[19-20]. In particular, Bergamo and Socco (2013) and Bergamo and Socco, 2016) have demonstrated on synthetic and field data, that for dry loose granular materials[18,21], where the Poisson's ratio is likely to be constant with depth and the velocity profile is an effective pressure driven gradient, the distance between fundamental and first higher mode exhibits enough sensitivity to Poisson's ratio to allow for its reliable estimate and consequence retrieval of P-wave velocity profile (See Fig.2).

Beside higher modes, if a significant contrast in P-wave velocity exists within the investigation depth, surface wave leaky modes are likely to be excited and gathered. Since leaky modes present dispersive behavior that depends mainly on P-wave velocity they can be used inverted, jointly to fundamental and higher modes, to retrieve both S- and P-wave velocity profiles. Pomarenko et al. (2013); and Znak et al. (2015) have shown that P-wave velocity can correctly be retrieved on synthetic and real data acquired both with impulsive and vibroseis sources[22]. The main limitation of the method is that dispersive leaky modes not often are retrieved in field data.

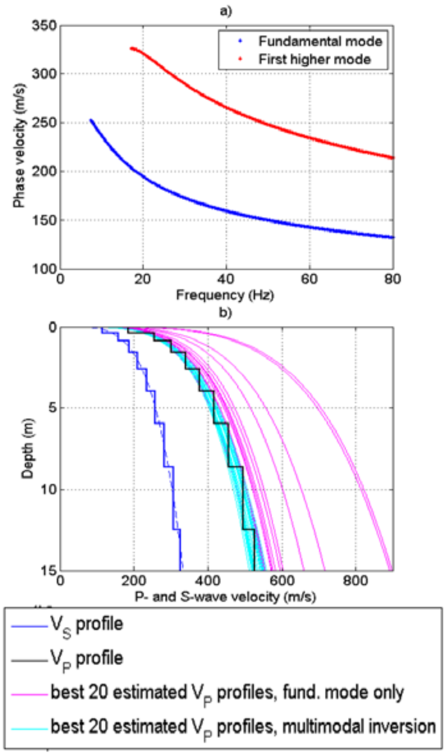

Fig.2 1D synthetic model simulating a dry loose formation with constant Poisson's ratio with depth: comparison of the P-wave velocity estimation obtained by inverting the fundamental mode only or the fundamental plus first higher mode of propagation.

IV. APPROXIMATED ROBUST POISSON'S RATIO ESTIMATION

Recently, Socco and Comina (2015) have shown that the relationship between the investigation depth of Rayleigh wave fundamental mode and dispersion curve wavelength can be linearized and used to predict directly the S-wave time average velocity[10].. In case of constant Poisson's ratio with depth, the value of Poisson's ratio can be exactly and directly estimated by comparing the experimental wavelength/depth relationship with theoretical analogous direction computed for different values of Poisson's ratio. In case of variable Poisson's ratio with depth the comparison with the theoretical relationships provides an approximated estimate which is still able to provide the P-wave velocity model with uncertainties below 10% (Fig.3). These promising techniques has been successfully applied to both synthetic and field data also accounting for lateral variations. This represent a novel approach to estimate near surface velocity models from surface waves.

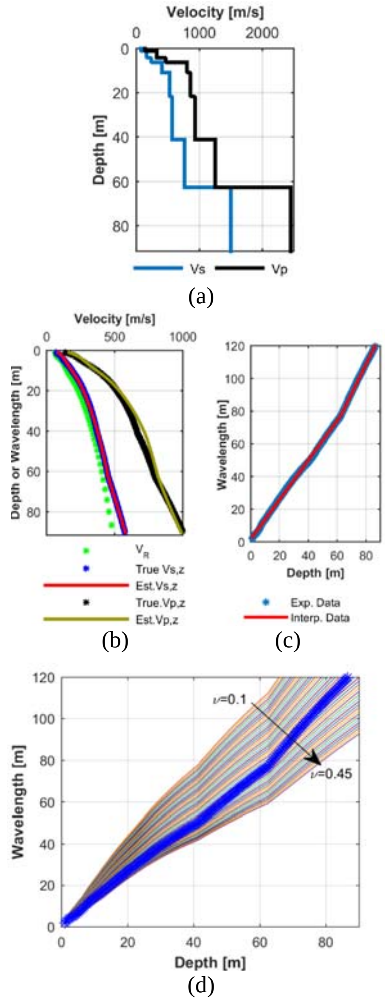

Fig.3 1D synthetic model: approximated direct estimate of time average P-and S-wave velocity profiles; (a)reference velocity model; (b) comparison between true and estimated P- and S-wave time average velocity, together with the surface wave dispersion curve plotted as a function of wavelength; (c) linearized relationship between investigation depth and wavelength; comparison between true wavelength/depth relationship and synthetic wavelength/depth relationship for constant Poisson's ratio[11].

V. CONCLUSION

Surface wave analysis is a recognized method to estimate S-wave velocity models of the near surface layers. Recently, in the view of using ground roll in seismic exploration data for estimating near surface velocity models, the interest of researchers have moved to the possibility of estimating also P-wave velocity models. Several approaches have been shown to be effective toward this task on simple 1D synthetic profiles. The extension to 2D/3D models is straightforward and in most cases already available in literature.

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