Robust static estimation from surface wave data

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Laura Valentina Socco, Guy Mabyalaht, DIATI – Politecnico di Torino; Cesare Comina, Università di Torino*

Summary

Ground roll of seismic data is mainly composed of surface waves. Surface wave analysis can be used to estimate near surface velocity models useful for static computation. We show, through a Monte Carlo inversion, that the static estimation is robust beyond the uncertainty introduced by solution non-uniqueness of surface wave inversion. Moreover we propose an approximated technique to estimate statics directly from surface wave dispersion curves without the need for inverting and retrieving the velocity model.

Introduction

Surface waves in seismic records are not anymore considered only noise to be filtered out during seismic processing. The potential of analyzing them to retrieve S-wave near surface velocity models has been widely recognized in recent years (Haney and Miller, 2013). The purposes of estimating the near surface velocity models can be several, but one of the most important in seismic exploration is the computation of long wavelength static corrections (Dulaijan and Stewart, 2010; Roy et al., 2010; Douma and Haney, 2011; Boiero et al., 2013).

The processing of surface waves is usually performed by extracting the dispersion curve from CSP gathers and then inverting the dispersion curve to estimate a 1D velocity model that can be used locally to compute the one-way time for static corrections (Socco et al., 2010a). Dispersion curves can be extracted using several wavefield transforms commonly available in seismic processing tools (Socco et al., 2010b), in case of lateral variations, spatial moving windows can be used to focus the extraction of dispersion curve and obtain dispersion which is representative of local properties of the subsurface (Bergamo et al., 2012). Inversion can be performed with deterministic or stochastic approaches. The non-uniqueness of the inversion solution is a well-known drawback of surface wave processing (Socco et al., 2010b) and hence it is very important to quantify the uncertainty that is introduced on static computation by this process.

The original idea of this study comes from a previous study aimed at estimating the effect of solution non-uniqueness of surface wave inversion on the computation of site seismic response parameters for seismic hazard evaluation (Foti et al., 2009; Comina et al., 2011). Here we use a Monte Carlo inversion code (Socco and Boiero, 2008) to analyze the effect of solution non uniqueness and then we propagate it to the computation of static correction. We analyze the uncertainties from a statistical point of view to compare the uncertainty on single model parameters estimation with those on the estimation of one-way time. Then we explore the possibility of making a fast and approximated estimation of the static correction without the need for inverting the dispersion curve.

Method

The inversion of surface wave dispersion curve is usually performed by assuming a local 1D layered model. In most of the cases density and Poisson's ratio (or P-wave velocity) of the layers are assumed a priori and inversion unknowns are only layer thicknesses and S-wave velocities. The inherently smooth nature of the dispersion curve makes the inversion poorly sensitive to single layer properties but, on the other hand, it provides a very robust estimation of the global behavior of the site (Comina et al., 2011) and, hence, the inversion becomes very robust when applied to the estimation of average parameters like RMS velocity and one-way time. To demonstrate this we perform the following:

- We compute a synthetic dispersion curve from a layered model and we invert it using a Monte Carlo inversion.
- We select the velocity profiles which can be considered equivalent from a statistical point of view and we consider them all feasible solutions of the inversion.
- We use all the accepted models to compute static corrections (one-way time) for datum plan located at different depths.
- We compare the uncertainties on the estimation of individual model parameters with those associated to one-way time.

The Monte Carlo inversion we use is thoroughly described in Socco and Boiero (2008). We invert dispersion curves by comparing them with synthetic modal curves of models which are built with random selected model parameters defined by uniform a priori probability density function. The synthetic dispersion curves are scaled to optimize the model space sampling (see Boiero and Socco, 2008; Maraschini et al., 2011 for details about the scaling) and are then compared with experimental curves through a chi-square misfit that includes experimental uncertainties. Inference on the model population is performed by applying a statistical test (Fisher test) to select accepted models which are statistically equivalent to the best fitting profile at a given level of confidence. The set of selected models provides hence a picture of solution non uniqueness of the inversion, since every model can be equally considered a feasible solution. The uncertainty on the final model parameters due to non-uniqueness can then be evaluated by statistical analysis of the posteriori probability density functions. Each model selected by Monte Carlo inversion is used to compute the static correction (one-way time) for different depths of the datum plan and the obtained values are compared with those relevant to the true model. In this way it is possible to evaluate the effect of the uncertainties due to solution non-uniqueness on the estimated static correction value.

After showing that the static estimation is robust, we propose an approximated way to estimate the static correction without the need to invert the data. Approximated relationships between investigation depth and wavelength of surface waves have been proposed in literature (Abbiss, 1981; Brown et al., 2000). We hence consider the relationship between the dispersion curve (expressed in wavelength vs. phase velocity) and the one-way time at different depths and we show, on synthetic data, that this relationship can be approximated by a linear equation. This linear equation, estimated for one dispersion curve with known V_S model, can then be used to predict an approximated one-way time for other dispersion curves of similar models.

Examples

Several synthetic models have been produced to simulate different possible near surface conditions: layered models with strong contrasts, smooth velocity gradients simulating loose sand over a stiff bedrock, layered model with low velocity layers. We here present a layered system with increasing velocity and high velocity contrasts. In Figure 1 we show the reference model and all the models selected by Monte Carlo inversion. In Figure 2 we show the dispersion curve relevant to the reference model compared to those relevant to the selected models. As it can be noticed, even if the model space has been set with the same number of layers of the true model, the selected models show a strong non-uniqueness.

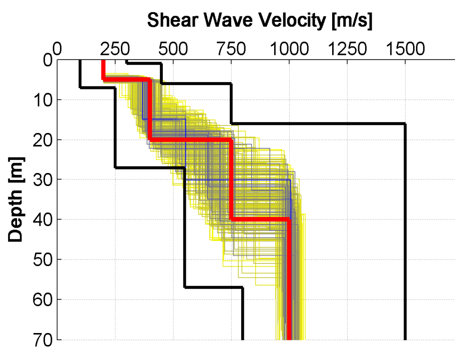

Figure 1: Monte Carlo inversion results: in red the true model and in colour scale the selected 200 models out of 10^5 simulations, the colourscale represents the misfit. The model space from which the random sampling is performed is indicated by black lines.

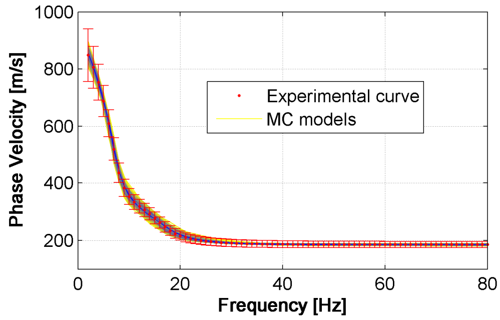

Figure 2: Dispersion curves: in red the one relative to the true model and in colour scale, representing the misfit, the synthetic curves relative to the selected models in Figure 1.

For these models, four different depths of the datum plan have been selected: 80 m, 110 m, 140 m, and 170 m and one-way time has been computed for all the selected models of Figure 1 and for the true model. The one-way time values are shown in Figure 3. In spite the difference among the velocity models the static values obtained from them are very close to the true value and the error is very small (below 4 %).

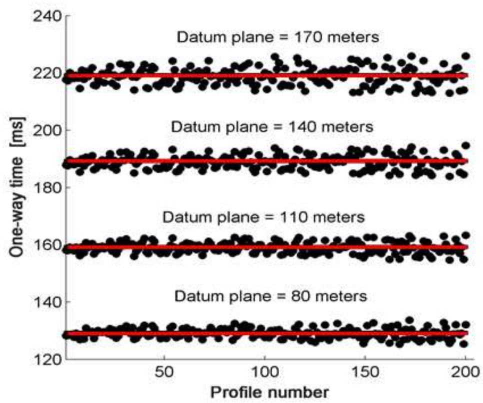

Figure 3: The one-way time computed for different datum plan depths using the selected V_S models of Figure 1 (dots); red lines represent the true values at different depths.

To compare the uncertainty on model parameters with those on the statics we consider more in detail the results relative to datum plan at 80 m depth. The histogram in Figure 4 shows the values of the estimated one-way time from all the selected models compared with the true value. The true value of one-way time for datum plan at 80 m depth is 129.16 ms and the normal distribution that fits the data has a mean value of 129.05 ms and a standard deviation of 1.68 ms. It is interesting to notice that 104 V_S models out of the 200 selected by the inversion fall within

± 1 ms difference from the true value of one-way time. Hence they have error lower than typical time sampling.

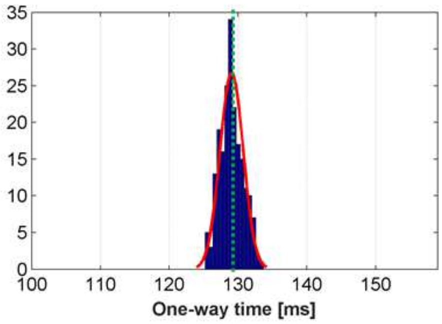

Figure 4 – One-way time for the selected models for datum plan at 80 m depth: distribution of the estimated values compared with true value (green line).

In Figure 5 we compare the misfit of one-way time for the selected models with the misfit relative to individual layers. For each layers of the selected model the one-way time is computed and then the one-way time for the whole model is computed. The misfit between estimated and true value is represented in form of box plots that provide a picture of the parameter statistical distribution by showing the median and an area that identifies the upper and lower quartile. The notches represent the uncertainty and dotted lines represent the extent of the population. Red crosses represent outliers. By comparing the one-way time computed for each layer with that obtained of the whole model we notice that, even though the uncertainties on individual model parameters is high, the uncertainty on the RMS properties of the model is very low.

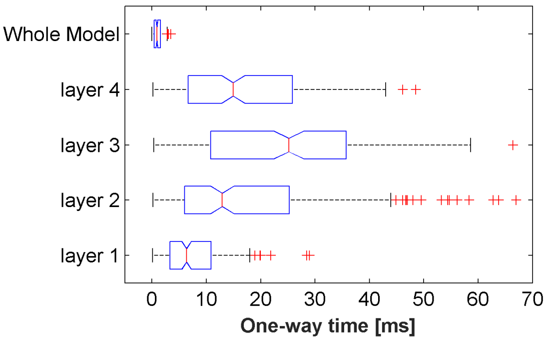

Figure 5 –boxplots of one-way time computed for the single layers and for the whole model for the selected models.

The results of previous analyses shows that dispersion curve is poorly sensitive to individual model parameters but it is strongly sensitive to RMS properties of the velocity model. This suggests that there is a strong link between the phase velocities of surface waves at various wavelengths and the RMS velocity of the V_S model at various depths. To exploit this link we perform another synthetic example.

We imagine that several dispersion curves have been extracted along a seismic line or over an area where the near surface is a layered system with variable velocities and layer thicknesses. To reproduce a significant variability, even greater than what geologically realistic, we have randomly generated a set of models (Figure 6) and we have computed the relevant dispersion curves. In Figure 7 we show both the RMS velocity as a function of depth and the dispersion curves as a function of wavelength for all the models.

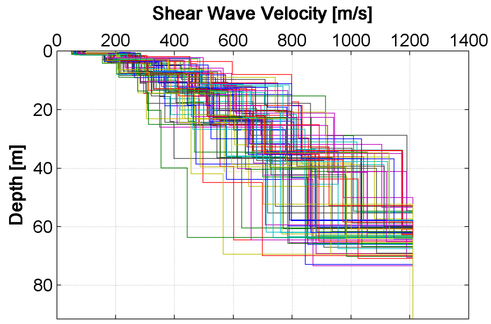

Figure 6 – Random generated models with varying velocities and layer thicknesses; the bedrock velocity is assumed constant.

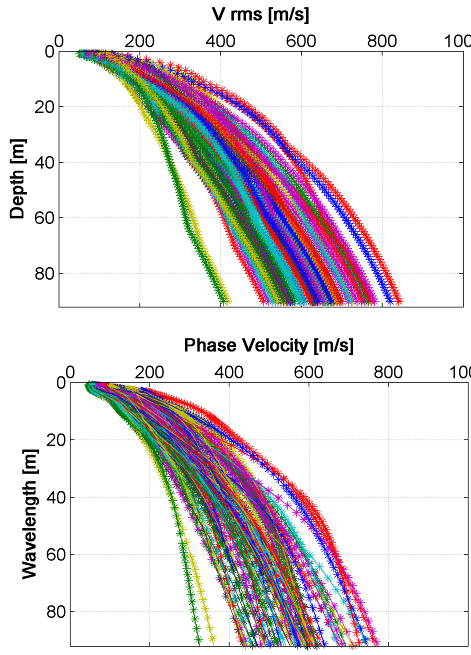

Figure 7 – Random generated models: top) V_{RMS} as a function of depth; bottom) dispersion curves as a function of wavelength.

In Figure 8 we show the plot of the dispersion-curve phase velocities vs. model RMS velocities with the assumption that wavelength is equal to depth. The plot shows a good correspondence of the velocities and a roughly linear trend.

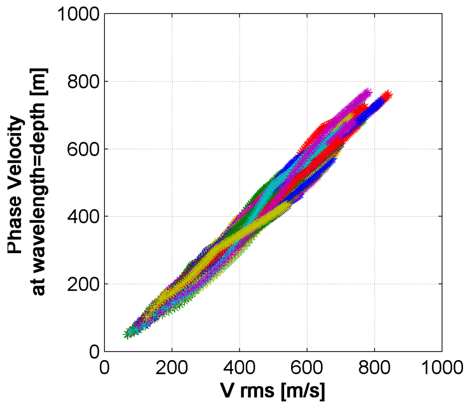

Figure 8 – phase velocity of dispersion curves versus model V_{RMS} for wavelength equal to depth.

We then assume that one of the V_S model is known (by inversion or thanks to a local direct estimation in a borehole) and all the others are unknown. One randomly selected model is hence used to estimate the linear relationship between dispersion curve velocity and RMS velocity via the wavelength: the dispersion curve is interpolated and, for each depth, the wavelength at which the phase velocity is equal to the RMS velocity is searched. Then the values of depth and corresponding wavelength are plotted and used to estimate the linear relationship. In figure 9 we show the linear relationship for the selected model assumed to be known.

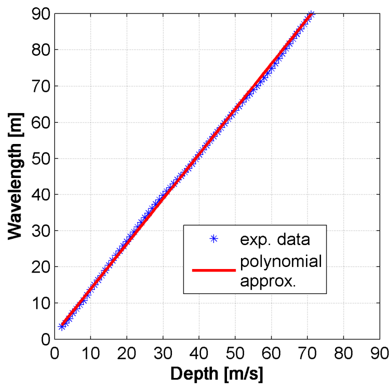

Figure 9 – relationship between model depth and dispersion curve wavelength; the data points are those for which the phase velocity corresponds to the RMS velocity of the model.

After estimating the linear relationship we use it to predict the RMS velocity and one-way time for all the other models assuming that the RMS velocity at a given depth is equal to the phase velocity of dispersion curves at the wavelength identified by the linear relationship. In Figure 10 we show prediction errors for all the models at different depths of the datum plan with respect to the true values. Even though the velocities of models' layer have variations of more than 100 % among each other's and the RMS velocity below the bedrock depth ranges from 350 to 830 m/s, the error on the estimated RMS velocity below the bedrock top is in the range of ±10%. For our synthetic models this corresponds to a difference between true and estimated one-way time of about ±10 ms.

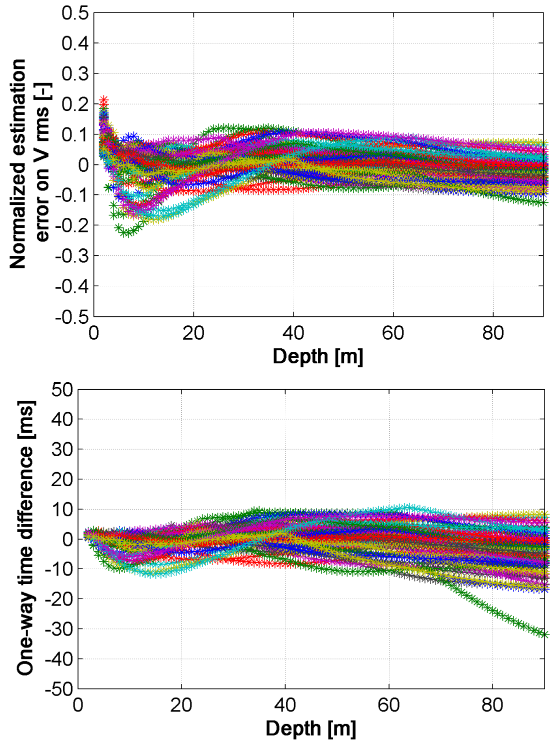

Figure 10 – top) estimation error of the RMS velocity for all the models; bottom) difference in one-way time with respect to the true value.

Conclusions

We have shown that the inversion of surface wave dispersion curve is a very robust tool for the estimation of static corrections (one-way time) regardless the inversion solution non uniqueness. We have then proposed simplified approach for the approximated prediction of the RMS velocity and one-way time based on the relationship between dispersion curve wavelength and investigation depth that, given the knowledge of one V_S model over a dispersion curve data set, does not need for dispersion curve inversion.