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# A CFP Approach to Estimate the Shear-Wave Velocity Distribution in the Shallow Subsoil

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## SUMMARY

The CFP approach has been used to estimate Green functions for a high- resolution shear-wave reflection field dataset. This data set contains lateral variations of the near surface and has very low velocities. To estimate a velocity model for this kind of data is not an easy task. The CFP approach gives one-way Green function times which are accurate as indicated by the flat events at t=0. These Green functions contain all the information needed to build an accurate velocity model.

## Introduction

Seismic shear-wave velocity ($V_s$) in the shallow soil layers is an important parameter in all dynamic loading problems, e.g., vibrations, moving trains, liquefaction and other earthquake-related issues. The knowledge of $V_s$ is necessary in various design and stability calculations in civil and geotechnical engineering. An in-situ estimate of the small-strain rigidity can be obtained from the field-measured $V_s$. Laboratory estimates on reconstituted or disturbed samples generally have large uncertainties. Traditionally, $V_s$ has been measured in the field by seismic refraction surveys or though analysis of seismic surface waves (MASW, SASW). These approaches have their well-known limitations. Vertical Seismic Profiling (VSP) or seismic cone penetration test (SCPT) offers reliable estimate of $V_s$, but this information is restricted to the test location. Shallow subsoil has often significant lateral variation in properties. In this paper, we propose a new approach based on analysis of Common Focal Point (CFP) gathers to estimate the laterally continuous $V_s$ field in the shallow subsoil.

The approach of CFP, introduced by Berkhout (1992, 1997); Thorbecke (1997), has been further developed under the DELPHI project of the Delft University of Technology. This technology has successfully been used for velocity independent redatuming Kelamis *et al.* (1999) and for estimation of Green functions and velocity models Kabir and Verschuur (1997); Bolte *et al.* (1999); Hegge *et al.* (1999); Brisbourne *et al.* (2000). In this research we have attempted to adapt for the first time this approach to shallow, high-resolution shear-wave seismic data. For shallow seismic data the CFP approach is well-suited due to the following reasons:

1. because of the significant lateral heterogeneity in shallow subsoil, the analysis of two-wave reflection times are generally complicated and the obtained results are less accurate; the one-way traveltimes used in CFP approach of velocity estimation are less complicated and easier to pick,
2. extra noise reduction is achieved by Fresnel stacking,
3. Green functions are estimated from data only, without the use of any velocity model, and
4. the tomographic inversion of one-way traveltimes can provide a smooth but accurate velocity model, which is suited for migration  an operation important for imaging correctly the reflectors and objects in the shallow sub-soil.

In the following sections, we shall first briefly outline the approach as adapted to shallow, shear-wave reflection data, and then present results on a recently acquired field seismic data-set.

## Brief outline of the approach

In the CFP approach every shot is first down-propagated to a subsurface reflection point by means of initial one-way Green function. This initial operator is constructed by using a homogeneous velocity, and placing a point source at a chosen zero-offset time. If the operator is correct then the constructed CFP gather represents seismic waveforms received at the acquisition surface due to a source which is located on the reflector. This is illustrated in Figure 1. Many such sources can be located along a reflector, and the upward propagating one-way times at each receiver is estimated.

The generation and updating of the initial Green functions is carried out by a genetic algorithm. In this algorithm the one-way times and Fermat's principle are used to calculate two-way reflection times which are matched in an optimal way with the data (Verschuur *et al.* , 2007). These initial operators are used to construct panels, which are manually picked to fine-tune the operators. During this stage the operators are updated until the differential time shift (DTS) panel contains flat events at $t = 0$. For a flat event at $t = 0$ the estimated operators represent the traveltime from a position on the reflector to the surface. Note that after the operator updating the spatial position of the operator is not known.

Finally, the one-way traveltimes of all picked reflectors are tomographically inverted (Cox, 2004) to obtain the velocity field in the shallow subsoil. During the inversion the algortihm

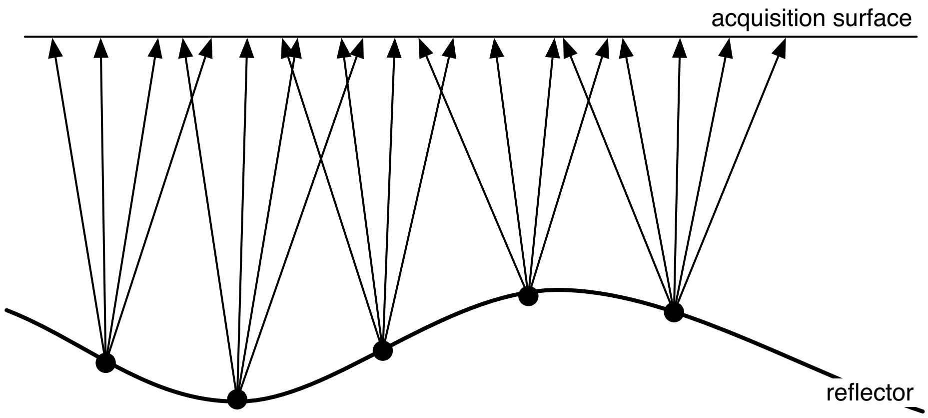


Figure 1: One-way Green functions for one reflector contain velocity information of the medium they travel through.

finds the velocities which explain the traveltime in the operators, and also calculates the spatial position. The flow chart of the whole approach is presented in Figure 2.

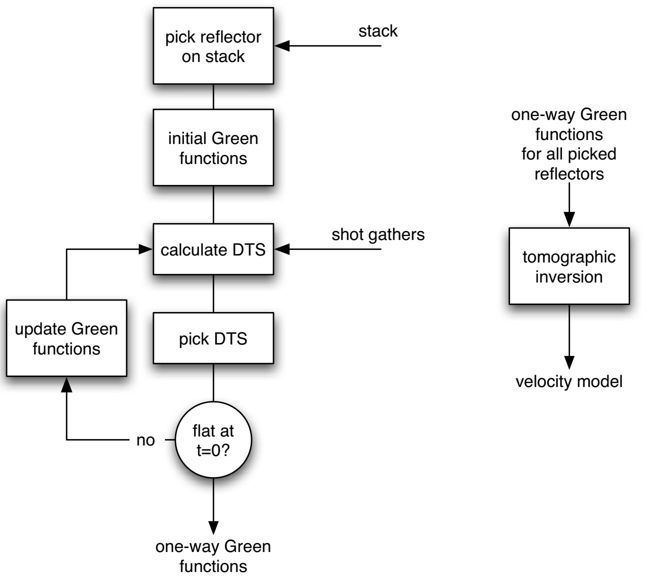


Figure 2: Processing flow for the estimation of Green functions for one reflector. This flow is repeated for all reflectors and all estimated Green functions are input to tomographic inversion.

**Shallow seismic reflection: field experiment**

A field experiment was carried out to acquire high-resolution shear-wave data. The electromagnetic shear-wave vibrator source (Ghose *et al.* , 1995) has been used in this experiment. The vibrator sweep was 20-400 Hz. For each shot the raw vibrograms were deconvolved using an accurate estimate of the groundforce generated by the source; the vertical stacking was performed after source-signature deconvolution (Ghose, 2002). The vertical stack count was 4. The source interval and the receiver interval were 0.5 meter. There were 72 single-component horizontal receivers for every shot. In total 181 shot positions were covered along a line, in one day of field work by two persons.

Figure 3(a) shows two raw shot gathers (representing the first and last part of the profile). Figure 3(b) shows the same two shot gathers after simple preprocessing. Preprocessing involved trace editing, geometrical spreading correction, spectral shaping, and AGC. Surface-consistent multiple removal was also performed (Verschuur *et al.* , 1992); the multiple energy was not significant in this dataset. The preprocessing of the data highlighted the reflection events. This facilitates subsequent estimation of the Green function by the CFP approach.

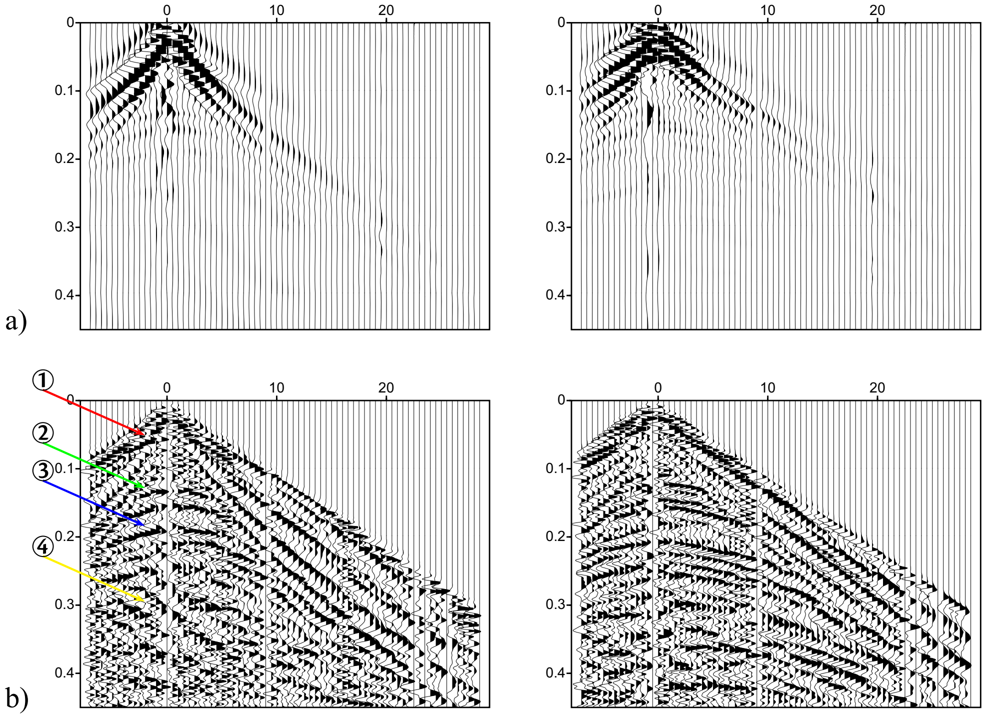

Figure 3: Raw (a) and pre-processed (b) shot records at positions 21.0 (left) and 56.5 (right). The four numbered arrows indicate the reflection events which are used in the CFP approach to estimate Green functions.

### CFP analysis of shallow S-wave reflection events

The Green function was computed for 4 reflectors (corresponding to the ones indicated in Figure 3b) following the CFP approach described earlier. The result for the second reflector before and after operator updating is shown in Figure 4. The events have been nicely flattened after application of the updated operators, which means the final estimated operators are correct. It is clear that the CFP approach works fine on such shallow S-wave reflection data. Therefore, the velocity field to be estimated in the next step by tomographic inversion of one-way travel times should be quite accurate. This work is now under progress.

### Discussions and conclusions

We have applied the CFP approach to high-resolution, engineering-scale seismic dataset. The approach is specially suitable for strong laterally varying near-surface seismic applications. Our tests on a recently acquired shear-wave reflection field dataset show that the approach works quite fine on such shallow seismic data. The events are nicely flattened and the one-way reflection times are accurate. This should lead to better velocity determination than those obtained from analysis of two-reflection data due to better S/N ratio and the simplicity of the events to pick. This high-quality one-way reflection times will enable one to obtain in the next step the shear-wave velocity distribution by tomographic inversion.

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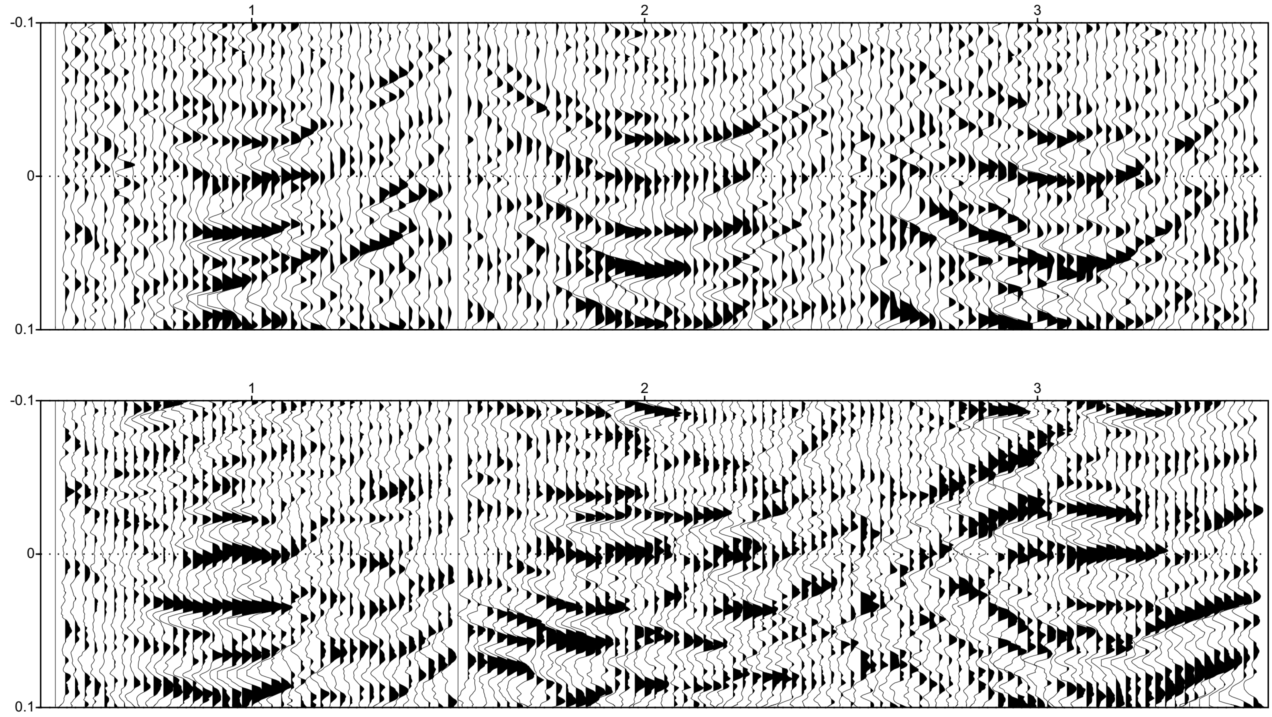


Figure 4: DTS panels at the second boundary before (top) and after (bottom) operator updating. Note the good alingment at $t = 0$ for the three position on the boundary after operator updating.

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