Introduction

The joint inversion method for arrival times of refracted and reflected waves is discussed in this paper. Nowadays this approach is popular and widely used for solving task of deep seismic exploration. Here we consider an algorithm of forward and inverse problems specialized for near surface seismics.

In engineering seismics there was many attempt separation of the reflected waves for extra information. It well known that using of refracted waves only, gives too rough velocity profile.

Unfortunately, in most cases of engineering studies, there is difficult to identify the reflected waves, because it is "noised" by other types of waves. Since the problem of identification of the reflected waves is an independent, complex direction - and will not be considered here. Let us assume that for our task, the first breaks and the time of arrival of the reflected waves for the n-th number of boundaries are known.

Forward problem

Forward problem - calculation the first arrival times and the arrival of the reflected waves for a model with an arbitrary velocity distribution and geometry of the reflector based on the Shortest path method (Moser, 1991). This method allows us to calculate the shortest ray path for refracted waves.

The combination of minimum paths from the source and the receiver to the reflector point allows the build path of the reflected wave for each boundary. Minimal total travel time from the source and the receiver is selected as a reflection point of the border. Using of this method removes the restriction on the complexity geometry of topography and the reflecting boundary and can be used for the interpretation of engineering seismics .

Forward problem has been developed for the two types of models. In the first case velocity section defined as a set of layers with arbitrary geometry boundaries and arbitrary distribution of the velocity inside each layer. The complexity of the boundaries is controlled by nodes number. Any boundary can be reflected and refracted, or only refracted. The advantages of this model type is the possibility of joint interpretation of P and S waves in a common geometry boundaries. Also, it is convenient to use for sparse observation systems.
In the second case, the model is divided regular mesh of cells with arbitrary velocity. Reflected boundaries are set arbitrarily and are not joined with the geometry of the cells. This type of model is useful for dense observation networks, such as seismic tomography.
Additional extra features of the algorithm includes the possibility of taking account of surface topography, anisotropy and the attenuation parameter.

Testing algorithm of forward problem was carried out for a number of analytical solutions and using other well known algorithms (Fig. 1). Shortest path method is based on graph theory, and has controlled accuracy, so when a sufficiently dense subdividing of boundaries could get accuracy less than 0.01 percent.

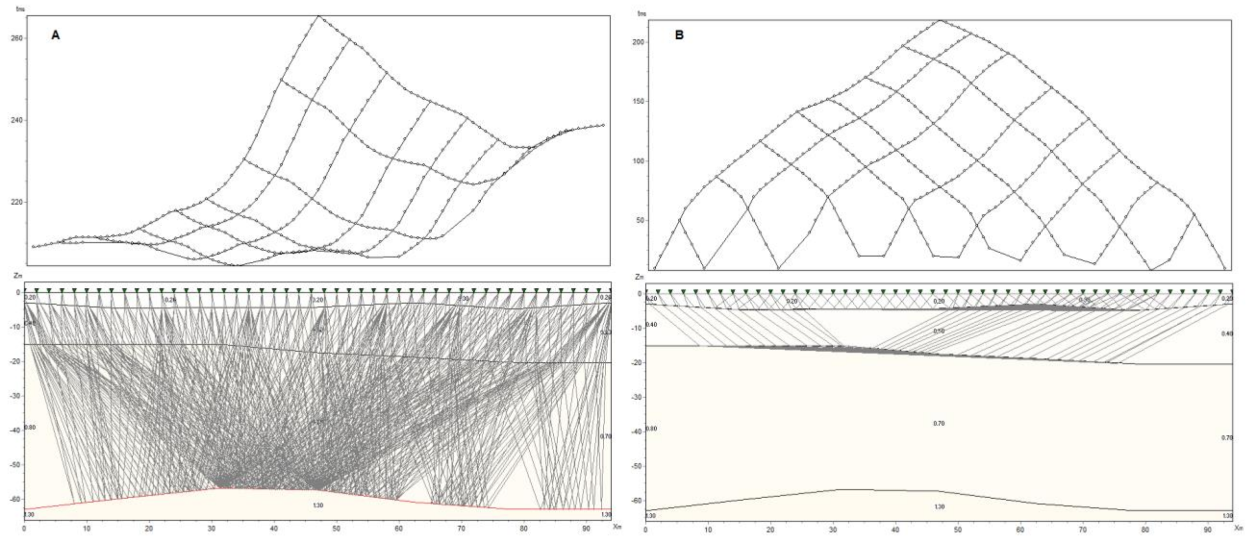

Figure 1 *Calculated reflected (A) and refracted (B) travel times curves and ray paths for complex velocity model.*

Inverse problem

For the inverse problem Occam inversion (Constable et all, 1987) procedure was used. The main problem with the joint inversion of velocities and geometry of boundaries is the difference of dimensions for this parameters. This negatively affects the properties of the matrix system. To reduce the dynamic range of the matrix - logarithmic norms of parameters (velocities and local thicknesses of layers and apparent velocities) were used.

Using of thicknesses instead the depths is allow to avoid the problem of boundaries intersection in the resulting model. Also, in order to suppress strong oscillations of geometry, an additional parameter controls the relative speed of change for velocity and thicknesses was used. Smoothing filter is constructed differently for the two types of models. In the first case, the operator is designed separately for each layer and works in the horizontal direction. In the second case the common filter is used for smoothing all cell's velocities and additional - for smoothing layer's boundary.

Algorithm testing

Inversion algorithm was tested on synthetic data (Fig.2) calculated for several types of velocity models. As a tested model - four-layer cross-section with arbitrary boundaries and the high-velocity object inside second layer was used.

Node sampling interval for boundary correspond to twice distance between the geophones. Observing system correspond to seismic tomography with shot point at each geophone. Directly before each inversion of synthetic travel times noise component was added.

Testing was performed as follows:

- In the first stage only first arrival times for the first and second types of models were inverted. The horizontally layered model with a constant velocity gradient was used as start.
- At the second stage only reflected times for the first and second types of models were inverted. The horizontally layered model with a constant velocity was used as start.

- In the third stage, the joint inversion for refracted and reflected waves data was carried out. In our experience, when working with synthetic data, to achieve acceptable data fitting, there is only three or four iterations enough.
- Finally, the inverted models were compared to the original.

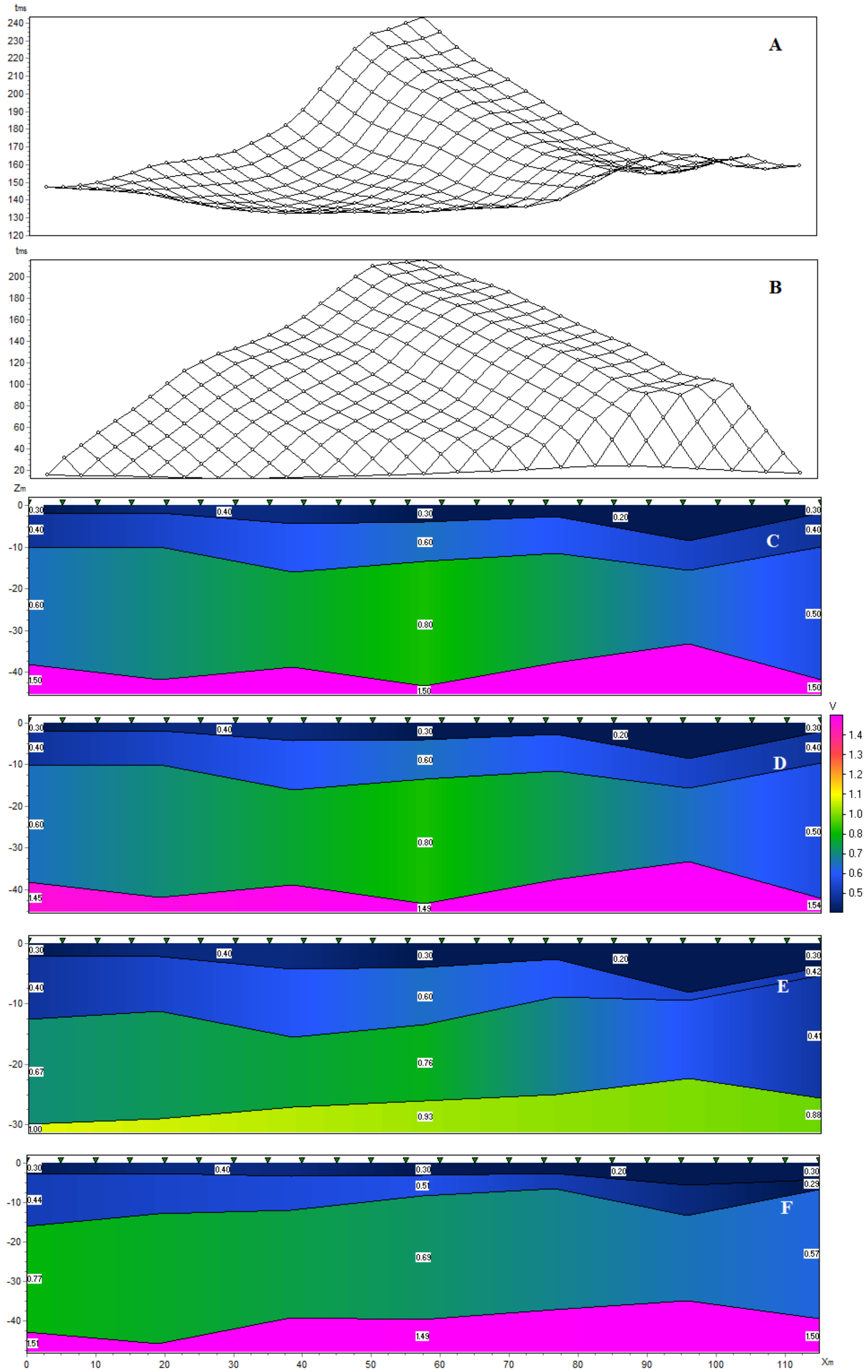

Figure 2 *Example of refracted and reflected synthetic travel times inversion. A – calculated reflection travel times data for original model C; B – calculated refraction travel times data for original model C; C – four-layers arbitrary velocity model with one reflections boundary(3); D – result of joint reflected and refracted data inversion; E - result of refracted data inversion; F - result of reflected data inversion. Before every inversion pass, noise was added to the synthetic data.*

Figure 2 shows the results of testing the algorithm for arbitrary layered model. This is a typical velocity section at engineering geophysical surveys. The upper part of the model consists of a low-velocity sedimentary rocks. The basis of the section is high-velocity rock formations.

Synthetic seismic survey consisted of 24 geophones spaced at 5 meters and shots in each geophones point.

The inversion was carried out until the RMS did not reach a specified level of noise. For this example, only 4-5 iterations was enough. The average computation time for each inversion was about two minutes.

As seen from the figure 2, the best results were obtained from the joint inversion of reflected and refracted data 2D. It is practically corresponds to the original model. With the one hand, using of reflection data allow to get the best rays coverage (for a more reliable determination of the velocity), on the other - it is better to recover the reflecting boundary geometry.

When the inversion carried out for reflected or refracted data separately, the model recovered considerably rougher. This is especially well seen for inversion of refracted data 2E. The lower boundary (reflected) shifted by almost 10 meters.

Test results for a number of models have shown significant improvement in the accuracy of recovering parameters in the joint inversion. Algorithm for joint interpretation of refracted and reflected travel times data was realized in the ZondST2D and is currently testing with field's data.

Conclusions

Proposed algorithm can be used for processing of shallow seismic data. The joint inversion of reflected and refracted travel times data significantly improves the quality of the resulted velocity sections. Using of refracted and reflected travel times data together allow to achieve greater depth of investigation.

Reference

1. Moser T.J., Shortest path calculation of seismic rays, Geophysics, vol. 56, no. 1, 1991.
2. Constable S.,Parker R., Constable C. Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data. 1987. Geophysics 52, 289.