TRAVELTIME DIFFERENCES IN SEISMIC REFRACTION INVERSION

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1. Introduction

The application of seismic refraction methods is very widespread in near-surface geological investigations for e.g. hydrogeological, geophysical engineering and geotechnical purposes [1], [2]. In a surface seismic measurement various source types can be used, related to which trigger error may occur during field measurements. If elastic waves are generated by explosion, an approx. 1-4 ms triggering error can occur due to the error of the geophysical blasting cap. Generating the waves with weight dropping or hammer strike, a piezoelectric ceramic or a geophone serves the trigger signal – cycle skipping may occur. These triggering errors can cause problems in the interpretation of measured data and the estimation of the parameters, especially in shallow explorations as the accuracy or the errors of the trigger time have greater importance there compared to that of deeper explorations.

This problem was examined earlier in the inversion of three-component seismic VSP surveys in a coal mine using the traveltime differences between the upper and lower geophone-triplet [3]; and in shallow seismic reflection exploration, estimating the shot distortion on each common shot gather and eliminating them by shifting all the traces [4].

In this paper the idea of double-trace data is applied to refraction traveltime data, a concept that was developed by Dobróka et al. [5] for tomographic interpretation. The modified conjugate gradient and SIRT algorithms proved to be effective for solving the problem described above. With this theory the problem of the inaccurate trigger time is attempted to be solved in the field of seismic refraction.

2. Traveltime differences in the forward problem

In the evaluation process of seismic measurements it is usually a problem that the measured traveltime dataset has some amount of triggering error originating from the inaccuracy of the source time. This problem mainly arises in seismological aspects where the measurement is continuous and the exact time of the wave generation is unknown [6]. However, the inaccurate trigger time also causes problems in the near-surface exploration of geological structures (seismic refraction methods) as in these cases relatively small traveltimes are measured that are comparable to the amount of triggering error occurring. Therefore all traveltime data related to the same source point have the same amount of trigger error, i.e. a certain value of time shift presents on the traveltime curves. In Figure 1 the problem of inaccurate source time is presented with an exact dataset and a dataset with trigger errors, in addition to the results of simple traveltime inversion and traveltime difference inversion.

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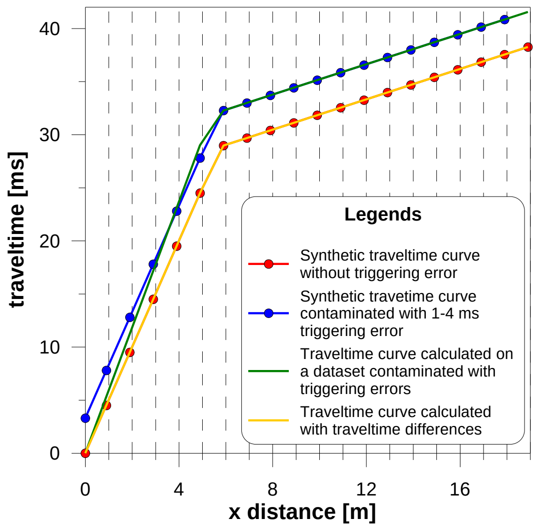

Figure 1. The representation of the evaluation problems of triggering errors in the traveltime dataset

To avoid the effects of this (1-4 ms) error, the interpretation of the data can be performed with traveltime differences instead of exact traveltime data. This idea was used formerly by Dobróka et al. [5] for tomographic interpretation with double-trace data. For solving the problem they used the modified conjugate gradient and SIRT algorithms.

The same concept is used in this paper for the interpretation of refraction traveltime data; therefore a certain receiver is chosen as a reference and traveltime differences (Δt) are calculated from all the other traveltime data related to the same source point:

$$\Delta t_{i,s}{}^{(meas)} = t_{i,s}{}^{(meas)} - t_{r,s}{}^{(meas)} \tag{1}$$

where $t_{i,s}$ indicates the traveltime data of a wave generated from the s-th source point and received by the i-th receiver (geophone); $t_{r,s}$ means the traveltime data detected by the reference geophone. Firstly a traveltime difference dataset has to be generated from the measured dataset and in the evaluation procedure there are several approaches to solve the inverse problem.

2. Inversion theory

Once a traveltime difference dataset is generated from the measured dataset the occurring inverse problem can be solved either for the original traveltime dataset or for traveltime differences. In this paper a solution is presented where traveltime differences are applied in the inversion procedure using the difference of the Jacobian matrices ($J_{i,s}$) calculated for the reference traveltimes ($G_{r,s}$) and the whole traveltime dataset ($G_{i,s}$). The idea is described in Eq. (2) with the same notations as in Eq. (1):

$$J_{i,s} = G_{i,s} - G_{r,s} . \tag{2}$$

The inversion method uses this newly calculated Jacobian matrix in the algorithm based on the damped least squares method:

$$\mathbf{m} = \left(\mathbf{J}^T \mathbf{J} + \varepsilon^2 \mathbf{I}\right)^{-1} \mathbf{J}^T \Delta\mathbf{t}^{(meas)} , \tag{3}$$

where **m** means the model vector, $\Delta\mathbf{t}^{(meas)}$ means the measured traveltime difference data, **J** means the difference Jacobian matrix of the partial derivatives of the traveltime data, and **I** is an identity matrix multiplied by the scalar damping factor ε^2. Applying simple ray tracing, only the first arrivals are taken into consideration in the inversion procedure and a two- or three-layered 1D structure can be interpreted. It had been proved that 1D inversion can be used to provide acceptable estimations when contoured cross-sections of 2D structures are constructed [7] and that local 1D forward modelling can be used for the investigation of 2D structures in the inversion of DC geoelectric data [8].

3. Synthetic Studies

In this paper an experimental study is presented to solve the problem of inaccurate trigger time (triggering errors) that occurs in seismic field measurements. As the method is under development, in this paper our investigations on 1D structure are shown.

A shallow (max. depth: 10 m), three-layered 1D geological structure was studied in an early step of this theoretical approach. A ‘measured’ dataset was generated on the exact synthetic model with FD-Vidale type ray tracing [9]. Thus a difference exists between the forward problem solution of data generation and our inversion algorithm. We contaminated this synthetic dataset (131 data) with 1% of synthetic noise of normal distribution (Gaussian noise) and a triggering error of 3-8 ms (a relatively huge amount of triggering error, differing for each source point). Therefore a highly erroneous dataset was created.

The traveltime dataset was ‘measured’ with a total of 41 receivers and the waves were generated from 5 source points. The same dataset was tested with the normal traveltime inversion method and with the method using traveltime differences. The results can be seen in Table I, where *D* means the data misfit (the relative distance between the measured erroneous and the estimated datasets), and *d* means the model misfit (calculated for the whole section) [10].

In Table I the values of *D* are somewhat misleading, as in general people tend to think that the data misfit has to be minimal at the best result of the inversion. In this case – as the ‘measured’ dataset is highly erroneous – the data misfit has less significance. In traveltime difference inversion the procedure is based on the minimization of the traveltime difference data misfit; results are shown in the second row of Table I (D_{td}).

However, the value of model misfit has a huge significance in this consideration, as it can tell us the real usability and efficiency of our inversion algorithm. In this value a number nearly 30 times smaller than that of the normal traveltime inversion can be seen as a result of traveltime difference inversion (Table I). This declares the usability and reliability of an inversion method calculating with traveltime differences for a three-layered 1D geological situation.

Table I. Results of the two inversion methods – tested on a highly erroneous synthetic dataset (contaminated with Gaussian noise and triggering errors)

	Results of **Normal Traveltime Inversion** Method	Results of **Traveltime Difference Inversion** Method
D [%] **Fit in Data Space**	40.1	102.9
D_{td} [%]calculated with traveltime differences	40.1	5.06
d [%] **Fit in Model Space**	**28.49**	**1.01**

Besides the values of data misfit, the fit of traveltime curves is also meaningful. In Figure 2 the fit of the erroneous dataset (red symbols) and the normal traveltime inversion results (blue lines) can be seen; and also the traveltimes calculated on the exact model (black rings). The misfits are eye-catching, especially if we consider the fact that the misfit has to be seen for traveltimes related to the same geophone (vertically). In Figure 3 the fit of the same erroneous dataset (green symbols) and the traveltime difference inversion results (orange lines) can be observed. In this figure, moreover, the poor fit of the exact dataset (black rings) and the inversion results can be noticed.

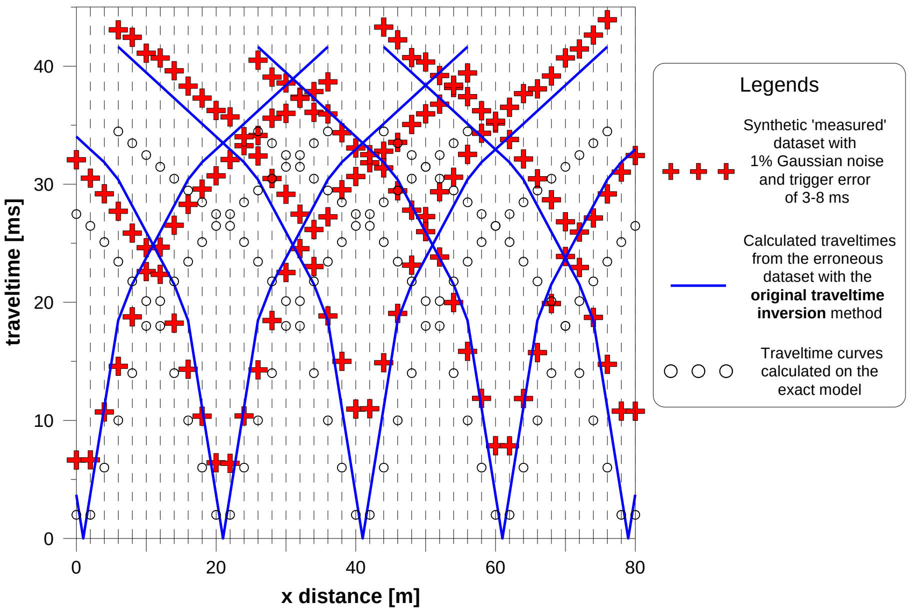

Figure 2. Results of the normal traveltime inversion method: D=40.1% (data misfit) from the measured erroneous dataset, and d=28.5% (model misfit) from the exact model.

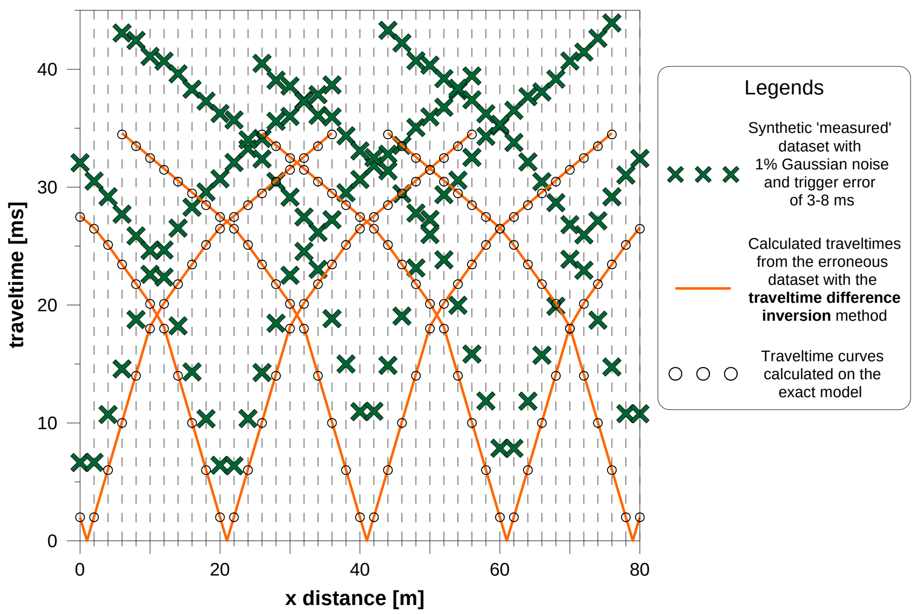

Figure 3. Results of the traveltime difference inversion method: data misfit of D=5.1% from the measured erroneous dataset and a model misfit of 1.0% from the exact model.

4. Field studies

Besides synthetic studies, a new method has to prove its usability on field datasets as well. The field measurements presented below were carried out in Izsófalva, in the North-Eastern part of Hungary. The elastic waves were generated with hammer strikes and detected by SM7 type 30 Hz geophones with 2 m spacing. Although the source time was triggered with a 10 Hz geophone installed directly adjacent to the source, a triggering error of approximately 1-3 ms occurred during the measurements.

The seismograms were processed with 10-200 Hz band-pass filter and an AGC gain using 70 ms window. The length of the evaluated sub-section is 34 m with 5 sources and 18 geophones, altogether 90 measured data (the field dataset has the same order of magnitude as the synthetic one above). According to our previous knowledge the investigated near-surface structure is nearly one-dimensional, with a gravely and a shaley layer, therefore the measured dataset was interpreted as a two-layered 1D structure (3 definable parameters) with both the inversion using normal traveltime data and that using traveltime differences.

A better fit was obtained using traveltime differences (calculated for traveltime differences). For traveltime differences $D_{td}=11.9\%$, while using simple traveltime data $D=17.6\%$. The relatively higher fitting error can be explained by the fact that structures in nature are hardly 1D; besides measurement errors, modelling error was also presented in these values of relative data distances.

5. Conclusion

Defining the accurate trigger time is usually a problem in refraction field investigations of near surface structures. However, by using a method that calculates with traveltime differences the error of source time could be highly reduced; therefore, the reliability of the results can be significantly better than that of the measured data. Assuming even 3-8 ms of triggering error in the synthetic case, the effects of the inaccurate source time disappeared. The method was tested on field data as well (measured above a nearly 1D, 2-layered medium). The results prove the usability of the new inversion method even in the case of in-line offset sources. The method will be further developed for 2D geological structures and its implementation is planned in the series expansion based multilayer inversion method [11], [12] developed formerly in the Department of Geophysics (University of Miskolc).

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