Improvements to shallow seismic velocity tomography method

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SUMMARY

The errors in seismic velocity recontructions in straight rays tomography method are unsatisfactory for the incompletely displayed seismic array around the panel. To improve resolution in these approaches, we propose a processing procedure consisting in re-applying the standard procedure after the obtained velocity model has changed. This modification is carried out based on the statistical analysis of the results obtained after the standard procedure was applyed for the first time. The procedure was tested on theoretical models and real data sets.

Key words: seismic inversion, shallow tomography methods, seismic velocity.

INTRODUCTION

The tomography based on velocity field analysis using straight rays (Mason, 1981; Neumann, 1981) is used with preference in mining geophysical investigations (Gendzwill and Stead, 1992) and engineering geology problems (Cristea et al., 2009; Bardan et al., 2010). Simply expressed, it can be argued that the principal problem of tomography in these fields is focused on identifying degraded formation enclaves with low velocities, located inside more compact geological medium characterized by higher velocities. Bardan et al. (2010) have studied the possibility to improve the resolution for inversion processing related to the coverage degree of field seismic array as regards the panel perimeter, implicitly to the homogeneity of raypaths coverage of the panel area. In the present approach is studied this problem for models characterized by high contrast between low (high) velocity anomalies and high (low) panel “background” velocity. As an advanced technology, a modular-procedure with two major components was performed: one which solves the forward problem and the other which gradually sums up three versions of the inversion processes in order to determine accurate velocity values. This processing technology is tested on data obtained by forward modeling and then it is applied on real data.

METHOD AND RESULTS

In tomography based on velocity field analysis two problems arise. The forward problem is the computation of the first arrival times of seismic rays propagating through 2D subsurface with given velocity variations. The inverse problem is the computation of a 2D velocity distribution, knowing the travel time of seismic rays through the subsurface. Certainly, in our case (considering straight line rays) there are no difficulties with the forward problem.

The analysis of the velocities field can be solved by an iterative process, developed by the following scheme.
- Establishing a working network, covering the entire area crossed by raypaths. The network cells, which are rectangles, should not be too large because of the risk of losing information when the problem is treated numerically.
- Initializing the calculation, starting from a basic model.
- Calculating theoretical arrival times for all raypaths for the considered velocity model and comparing them to measured times.
- Adjusting the velocity values of the model with the differences between the mentioned times, and starting again the new model calculation. This iterative process continues until a convergence criterion is satisfied.

We note the number of raypaths with R, and with M the number of velocities actually present. M is at most equal to the number of cells in the network. In this process, an iterative sequence consists largely of two steps.
1. Solving the direct problem by calculating the raypaths and the theoretical times. These times are calculated by adding the fragmentary times corresponding of each cell transited by the seismic ray, knowing the velocity and the segment of ray associated to the cell. For all raypaths we calculate the difference between theoretical arrival times and measured times. These differences are represented by Δt, which is a vector with R components.
2. For the inversion processing we describe a matrix algorithm (Bois et al., 1971). We consider the matrixes A and Ω. Coefficients of matrix A, which has R rows and M columns, are evaluated based on the elements obtained from solving the direct problem. Coefficients of matrix Ω, which has M rows and M columns, are integers which affect the calculation of velocities in a way that will lead to coherent values for velocities in adjacent cells. By solving the equation

$$(A^* A + \lambda_{opt}\Omega)\Delta V = A^* \Delta t, \qquad (1)$$

the vector of R components ΔV is determined, which adjusts the velocity values of the model. The next iteration recommences with the new velocity model, till the convergence criterion is fulfilled.

In equation (1), A* is the transposed of the matrix A and λ_{opt} is a positive number for the stabilization of equation solving system. Of course, equation (1) is deduced on a basis that the new model of velocity leads to theoretical times closer to the measured times (in terms of mean square error).

The resolution in determining the velocities field using the matrix inversion algorithm depends on the coverage of seismic array in relation to the perimeter of the investigation panel. To evaluate and improve the resolution we have proceeded as follows. The algorithms of the direct problem and that of matrix inversion are applied to a velocity model. The algebraic sum of the differences between the initial times and the iterative calculation of times is carried out using a subroutine. By following the evolution of this parameter it is possible to establish the optimal number of iterations of the matrix inversion algorithm which is based on minimizing the mean square error. In cases of a incomplete seismic array, the reconstruction of the velocity field by applying the matrix inversion process has large deviations. In these cases we propose a procedure to improve the results of processing by the modification of the obtained velocity modes. This modification is based on a velocity histogram. After this change, the iterative cycle of the matrix inversion algorithm is repeated. The modification of the velocity model consists of conserving values of the lowest (highest) velocity, while the remaining field is filled with values resulting from the application of the average velocity process to the initial model. The average velocity for a cell is the average of the velocities of the rays which crossed that cell.

The procedure is tested using the synthetic model of a medium characterized by a high velocity (4000 m/s) containing three custom-defined enclaves with a low velocity (2000 m/s). Figure 1 shows the results obtained by the matrix inversion method for a data set acquired on a recording array located completely around the panel. After the complete number of iterations the initial model is identically reproduced. Figure 2 shows the results obtained by the matrix inversion method (a) and by our procedure (b) for a dataset acquired on an incomplete recording array (seismic sources and receivers on the two opposited sides of tested panel). The obtained results of our procedure (Figure 2b) reveal an important improvement of the resolution. Thus, the lowest velocities are reproduced with relative errors of up to 1.5% and the highest ones with relative errors of up to 4%. The procedure is also tested using the synthetic model of a medium characterized by a low velocity (2000 m/s) containing three custom-defined enclaves with a high velocity (4000 m/s). Figure 3 shows the results obtained by the matrix inversion method (a) and by our procedure (b) for a dataset acquired on an incomplete recording array (seismic sources and receivers on the two opposited sides of tested panel). The obtained results of our procedure (Figure 3b) reveal also important improvements of the resolution (about three times for the anomalous velocity and about seventh time for the background velocity).

Our procedure is tested for an application with real data. Seismic research to salt mining has a wider range of applications (Gendzwill and Stead, 1992) that include tomography for pillars and inter-levels roofs inside the mining works. Similar investigations have been performed in Romania. An example is illustrated for the case of a pillar-base from Praid salt mine, Harghita county (+240 m horizon). Mining conditions have enabled the use of a quasi-completely device, the small restricted area on the right side of the panel being prohibited for mining work progress due to a weak-compacted volume of salt. Seismic field system (Figure 4) leads to the reconstitution of true velocity distribution using the matrix inversion algorithm (Figure 4a). The veracity of the result is illustrated by the individualization of the area with smallest velocity values on the right side of the panel, where the mining works were halted due to the above-mentioned degraded salt mass.

In the following sequence, the real acquisition data is considered for the fragmented field seismic system, retaining only the down side receivers and the upper part seismic sources in order to obtain a quasi-isometric shaped panel. Thus, it is simulated an incomplete seismic array related to cover the panel perimeter, which implies the application of our procedure.

The results reproduce with accuracy the velocity values (up to an error of 2% for the lowest values and up to an error of 1.5% for the highest values, see Figure 4b).

CONCLUSIONS

We have presented a procedure to improve the resolution in the determination of the velocity field using tomography data acquired on the incomplete seismic array as regards the panel perimeter. The tests on models of forward problem have shown great accuracy in restoring the distribution of seismic velocity values in the tomography method, with errors up to few percent. Certainly, the relative errors for the same observation system depend of the range defined by the extreme values of velocity for the analyzed model. The practical example has confirmed the accuracy potential of the proposed procedure. Also, it has proved the capability to reveal with accuracy the enclaves characterized alike by low and high velocities.

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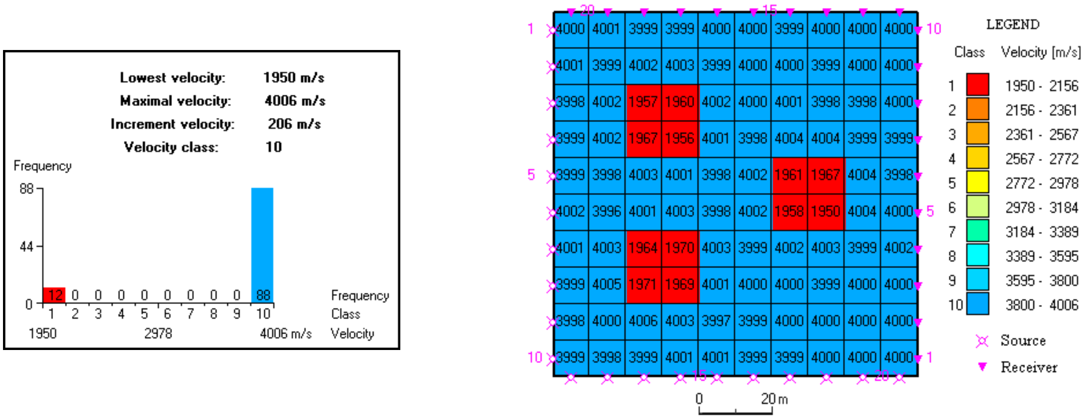
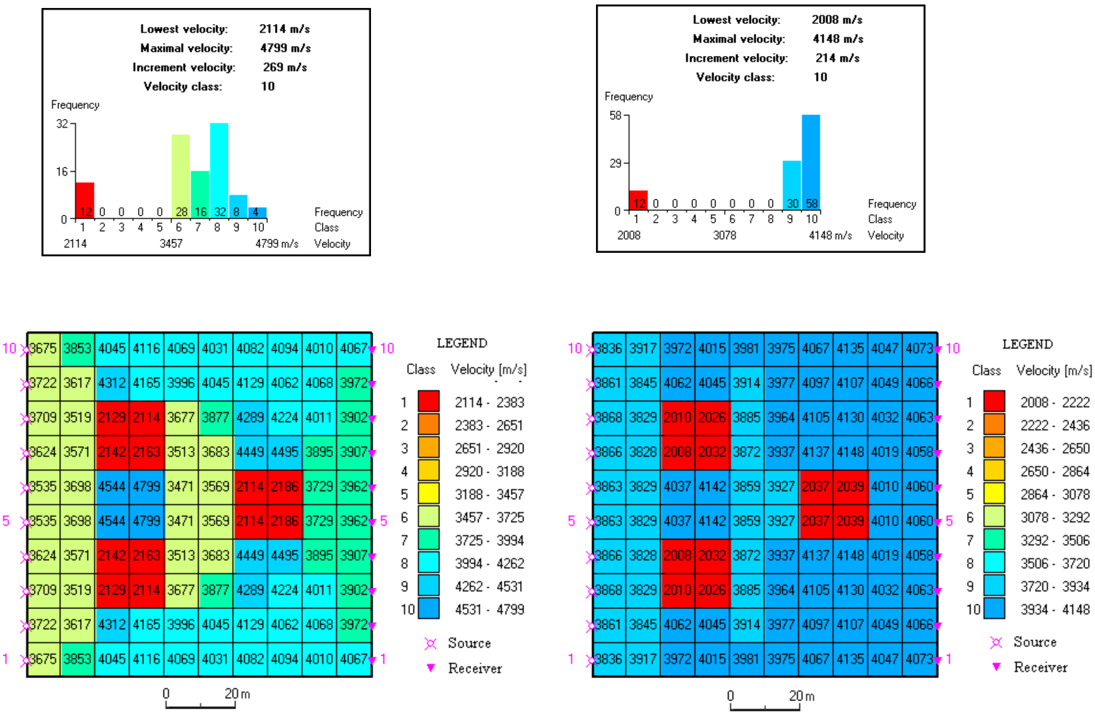
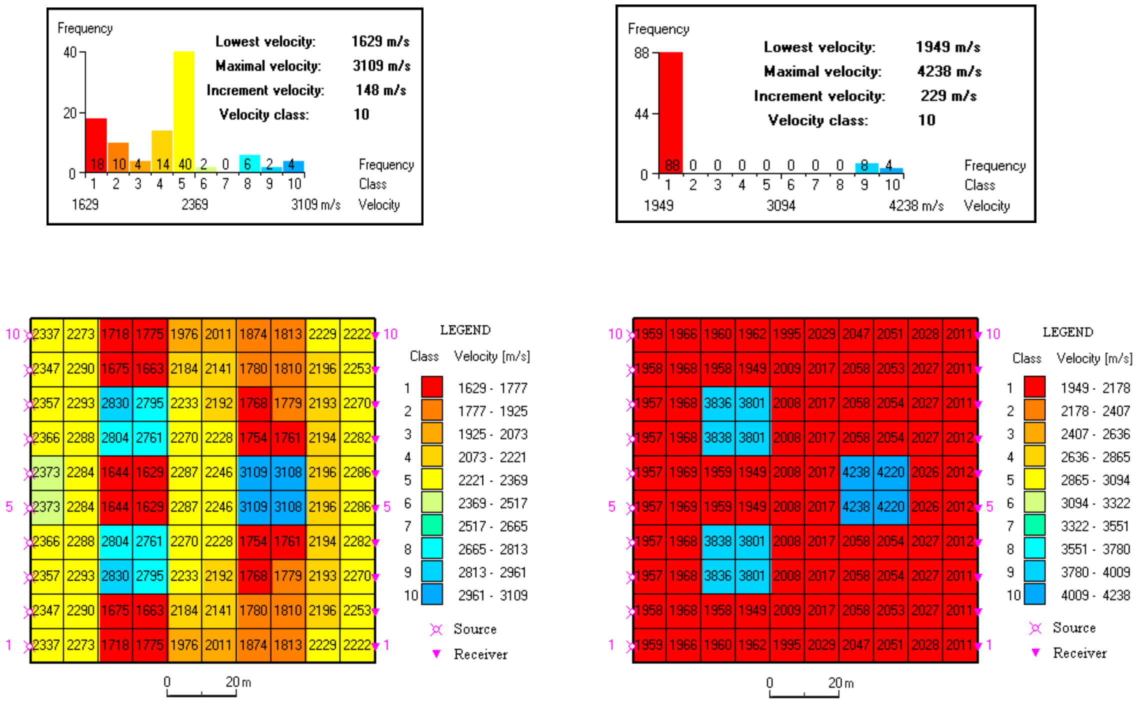


Figure 1. Tomography inversion for the model of a medium characterized by a high velocity (4000 m/s) containing three custom-defined enclaves with a low velocity (2000 m/s). This figure represents the results obtained by the matrix inversion method for a data set acquired on a recording array located completely around the panel: the histogram of velocity values (left) and the plan view of the velocity distribution (right).



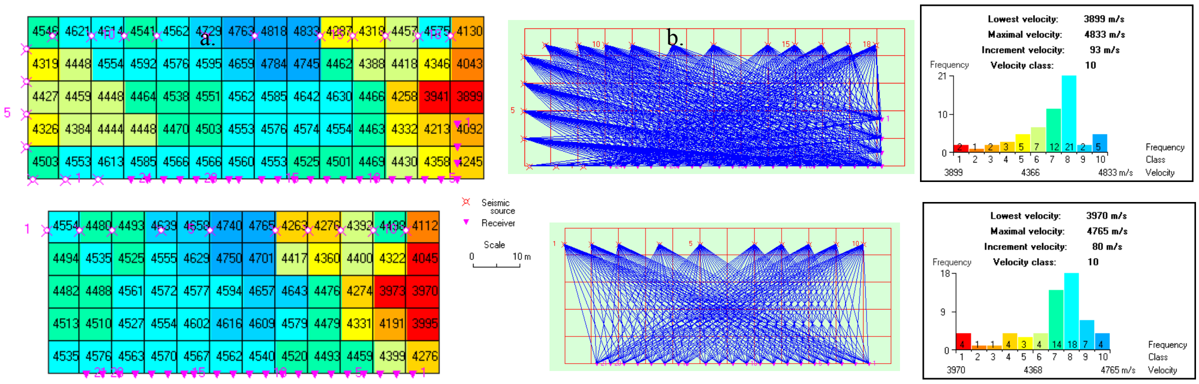
a. b.

Figure 2. Tomography inversion for the model of a medium characterized by a high velocity (4000 m/s) containing three enclaves with low velocity (2000 m/s). This figure represents the results obtained by the matrix inversion method (a) and by our procedure (b) for a dataset acquired on an incomplete recording array (seismic sources and receivers on the two opposited sides of tested panel). On the upper row are depicted the velocity diagrams and on the down row the velocity maps are illustrated.



a. b.

Figure 3. Tomography inversion for the model of a medium characterized by a low velocity (2000 m/s) containing three custom-defined enclaves with a high velocity (4000 m/s). This figure represents the results obtained by the matrix inversion method (a) and by our procedure (b) for a dataset acquired on an incomplete recording array (seismic sources and receivers on the two opposited sides of tested panel). On the upper row are depicted the velocity diagrams and the down row the velocity maps are illustrated



a. b. **c.**

Figure 4. Velocity tomography results for a pillar situated at +240 m horizon of Praid halite mine (100 km N. Brasov, Romania). Comparative results for the same panel in case of a quasi-complete seismic array surrounding panel (upper row), respectively simulated incomplete field array (bottom row). The columns represent: a. the plan view of the velocity distributions; b. the raypath panel coverages; c. the histograms of velocity values.