The Location estimation of seismic wave propagation layer velocities

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Abstract. On the basis of the original location-based technology developed by the authors for constructing seismic images of the deep structure of the earth's interior, a method is proposed for estimating the seismic wave propagation layer velocities. The technology ensures the unambiguity and stability of seismic imaging by successively solving direct kinematic problems for all reflecting boundaries. It consists in locating the reflection pulse's sources from the boundaries of the deep section's layers and restoring the kinematic parameters of the layers through them. To assess the next layer velocity, information is used on the parameters of the preceding boundaries and the direct kinematic problem's solution with the additional equality's condition of local velocities at the reflection's points from the underlying boundary.

1. Introduction
The actual seismic exploration’s task is the construction of seismic images, such as seismic maps of vertical and horizontal seismic sections, time sections, fracture zones arising from hydraulic fracturing, data cubes, etc.

The method of reflected waves plays a major role in seismic prospecting, and the methods of seismic imaging using this method possess high accuracy and reliability of the information obtained.

Currently, most seismic imaging technologies rely on the solution of the inverse kinematic seismic exploration problem (IKP) on reflected waves. The solution of the direct kinematic seismic exploration problem (DKP) is much less frequently used.

Solutions of these problems are sought within the geometric seismic framework of longitudinal reflected waves. It uses the temporal field’s kinematic parameters of seismic waves (the shape of the rays and the reflection isochron for all seismic traces) propagating in the geological medium from oscillation’s point source, to estimate the velocity and geometric parameters of this medium.

This approach is a limiting case when in the wave equation the wavelength tends to zero, which schematizes the process of wave propagation, highlighting, above all, the energy’s movement of the seismic pulse as a whole.

IKP consists in finding the spatial characteristics of the deep layer’s boundaries, on the assumption that the propagation trajectory’s type of the fronts, the velocity and arrival times of seismic waves on the seismic receivers, and the curvature’s characteristics and roughness of these boundaries are specified.

The IKP solution is possible only within the framework of some a priori assumptions regarding the structure and the studied medium’s properties. The system of such assumptions, which includes empirical data and known physical laws that control the deposit’s formation and the formation of their properties’ formation, is used to create a seismic-geological the environment model.
Modern methods of solving IKP use a layer model of the environment. It is believed that the structure model of the Earth is a layers’ set of rocks with different elastic properties, the velocity of which, as well as the boundaries’ properties separating them, are functions depending on parameters.

Solving the IKP means choosing a medium model and estimating its parameters so that the result of the DKP solution coincides with the received arrival reflection pulses' times from the deep layers’ boundaries of the medium. In fact, the initial arrival times of seismic pulses are known not precisely, but with some errors. Therefore, as a criterion for the solution of the IKP, it is used not the best, but acceptable coincidence with the observed times [1].

Inverse problems are incorrect, they violate at least one of the conditions for the solution to be correct - these are the existence conditions, unambiguity and stability of the solution. Therefore, even an approximate solution of IKP is possible only within the framework of some a priori assumptions regarding the structure and properties of the studied medium.

There are many algorithms for approximate IKP solution. By approximate solutions, parameters of only integral temporal model’s characteristics, such as average, effective velocity, average velocity gradient over depth and / or distance, can be estimated.

However, the experience of using these algorithms shows that with the same observations, the solution’s results may differ significantly from each other, which are a lack’s consequence of unambiguity and / or structural instability of the IKP solution [2].

To determine the kinematic parameters of the studied geological environment, various the hodographs’ approximations of the target seismic waves for the selected reflecting boundaries’ model are used. In order to restore individual seismic boundaries, compensation is required for the errors of these approximations, which is implemented by introducing kinematic corrections into the seismograms.

These procedures are uncertain and their implementation is associated with subjective decisions.

Modern studies of the deep environment structure are aimed at the continuation of the wave field obtained on the observation’s surface, in the direction opposite to the waves’ propagation - the migration of seismic wave fields.

A variety of complex computational procedures for seismic migration are performed in the temporal or deep region. But all of them are based mainly on the simplest horizontally layered model of the medium and the averaged parameters of its characteristics.

With more complex models, the results of constructing the migrated depth-velocity environment model are also subjective, especially when the migrated data are trying to be linked with the well data to better fit.

The presence of the proposed model parameters leads to the incorrect usual solution problem - there are many models that, satisfying the registered data, can lead to the same result.

For these reasons, IKP solutions can lead to poor quality estimates of the depth-velocity model’s parameters of the environment.

DKP is to find the pulses’ arrival times to seismic receivers, if the medium’s depth model, the propagation path’s type of the wave front, the receivers’ position and the source are specified, the moment of seismic oscillations is known. In most cases, the direct problem is quite simple and reduces to an explicit system’s solution of parametric optimization equations.

Solutions of direct problems are unambiguous and, within the limits of permissible errors, are stable. When solving the DKP, the propagation velocity of seismic waves from an oscillations’ point source is not a presumed parameter of the medium model, but becomes a secondary calculated parameter.

2. Problem definition

The technology’s basis of seismic imaging is information collected on the observation’s surface about the temporal field of seismic waves reflected or refracted from the deep layers’ boundaries. This field is recorded by seismic receivers at a constant position of the excitations’ source (explosion or vibrator).
Reflected from the deep boundary of the medium seismic waves are recorded at the points of the profile or observation’s area. They are presented in the form of seismic traces (time series) that define the waveform in the form of seismic pulses. Each seismic trace is the result of the waves’ interference arriving at the seismic receiver.

In [3], an original location-based seismic imaging technology, free from the impropriety arising from the IKP, is proposed. It uses unambiguous and structurally stable DKP solutions based on the coordinates’ location of the seismic pulses’ sources reflected from the deep layers’ boundaries of the medium under study.

Compared to the main seismic survey method - the common depth point method, location technology requires a significantly smaller number of vibration excitation points. It does not need to calculate the reflection time-distance curves, select the kinematic corrections and conduct the migration procedure.

The location is based on the superresolution detection’s idea of reflected pulses used in radio and sonar [4, 5]. The location is made by the arrival times of seismic pulses found on the seismic traces. It consists in detecting these impulses’ sources lying in the nodes of a given location grid covering the reflecting boundaries of the studied geological environment’s layers.

The grid locations’ coordinates, in which sources of seismic pulses were found, are used to build reflective boundaries of the layers.

Thus, the joint use of the reflected waves’ time field obtained from the observed data and solving the problem’s result of detecting the reflected pulses ensures the correct and seismic images’ stable construction.

Estimate of the propagation velocity of elastic waves in seismic exploration is given much attention.

Using the well-known form of the propagation trajectory of the wave front in the medium, one can calculate the velocity with which the seismic pulse moved from its source to the seismic receiver, penetrating through all the studied medium’s overlying strata.

Without knowledge of the seismic waves’ propagation velocities, neither a geometric nor a dynamic interpretation of seismic data, as well as their geological interpretation, is possible. Data on velocities in real environments can be used in solving many geological and geophysical problems, since the dependencies of velocity on geological factors and the velocity’s relationship with other physical properties of the studied medium are known [6].

The purpose of this work is to unambiguously and robustly find the propagation rates’ estimates of seismic waves in each layer of the medium deep model under study.

3. Estimation of layer velocities
The paper uses an example of model data for the simplest layered 2D seismic survey model consisting of four reflecting homogeneous isotropic layers’ boundaries (Figure 1).

In this model, monotypic reflected plane waves propagate from a point source of oscillations along rays in the form of straight lines, which corresponds to a constant seismic pulse velocity. The parameters associated with the dynamics of the excitation and propagation of waves, as well as changes in the shape and seismic pulses’ interference, are considered ideal.

According to field data, subjected to pre-treatment in the form of cleaning from noise and interference, gain control, identifying the type of seismic pulse and much more, a seismogram (set of seismic trace) is formed that characterizes the time field of reflected waves created by a point source of vibration excitation. It is believed that these procedures are performed and the arrival times of seismic pulses are already known with a one millisecond’s accuracy.

Locating sources of seismic pulses is carried out by placing excitation points (EP, several units) and reception points (RP, several dozen) - seismic receivers located on the earth's surface in a straight line at equal distances from each other. This set is used as a seismic antenna array (SAA). To improve the range resolution, the total number of SAA seismic receivers is divided into groups.
The basis of the location technology of seismic imaging [3] is based on two algorithms. The first, designated as A1, is a parametric optimization algorithm that solves the DKP in order to determine the possible sources’ coordinates of reflected seismic pulses on a given fragment of the location grid. It calculates the rays and travel times along them from the excitation source to the SAA seismic receivers, in turn for each layer. This calculation requires estimating the propagation velocity of seismic waves in each layer. The velocity in the first layer \( V_1 \) is considered known.

The location grid covers the reflecting boundaries of the medium and, in the simplest case, has the “beams” form of straight lines with multiple angles of inclination, whose centers are located on given horizontals and verticals of the deep environment. These straight lines serve to simulate a segment of the desired reflective border. In Figure 2 given a simplified (not shown a lot of straight lines degrading the visual representation, reduced to 8 the number of seismic receivers in the SAA group) grid fragment’s scheme location of the third border. It contains three "beams" located on three horizontals and one vertical (2350 m), and an image of the true boundary, represented by a black curved line. For all seismic receivers in the SAA group, 8 circles are plotted on each straight line depicting possible sources of seismic pulses.

The second A2 algorithm is the detection algorithm itself, which selects the coordinates of the best source using the idea of Capon's angular superresolution [7]. The idea is that the source is not detected by focusing the entire SAA or its group on a specific node of the location grid, but uses focusing the SAA group simultaneously on all the elements of the node vector to select the best element.

Algorithm A1 gives the coordinates of the elements of the node vector, and the A2 algorithm calculates the values of the decision function in them. The graph of this function is called direction-finding relief. In Figure 3 shows an example of three direction-finding reliefs belonging to three horizontals (different colors of lines) and straight lines with different angles of inclination. The blue color represents the best relief, and the best straight line has a slope of +4°.

The vector’s element of nodes with the maximum relief value determines the inclination angle of the straight line, which is considered to be selected. The procedure for selecting the best node is performed for each seismic receiver in the SAA group. For the selected nodes, indicated by green stars, an approximation of a rectilinear boundary’s segment is constructed. It is represented by the magenta color; squares are drawn on it, the coordinates of which correspond to the DKP solution for each seismic receiver of the current SAA group. Later, from the set of such approximations, a polynomial approximation of the entire boundary is constructed – the green line on Figure 4. A fragment of the true border is depicted in black.
The accuracy of the approximation of the obtained boundaries was estimated by the equation

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (y_i - f(x_i))^2}{n-1}},$$

where $y_i$ is the value of the $i$-th sample of the true boundary, $f(x_i)$ is the value of the $i$-th sample of the boundary's polynomial approximation, $x_i$ is the coordinate of the $i$-th samples, $n$ is the number of samples. The values are as follows: $SD_1 = 0.88$ m, $SD_2 = 1.86$ m, $SD_3 = 10.84$ m, $SD_4 = 0.01$ m.

In this way, it is possible to detect the sources’ coordinates of seismic pulses and the shape’s approximation of the reflecting boundaries of all the layers that precede the one in which the layer velocity is estimated.

To construct the next layer’s reflecting boundary of the medium’s depth model under study, it is necessary to estimate the propagation velocity of seismic waves in it. For this purpose, several deployments of EP and RP are used. In Figure 5, in order to facilitate the visual presentation, only two EPs and four RPs are shown, used to locate the underlying boundary of the fourth layer. In the Figure, green stars have the same meaning as in Figure 4.

Polynomial approximations of all overlying boundaries and estimates of the layer wave propagation velocities have already been calculated. To estimate the fourth rate, the modified A1 algorithm is applied to all layouts. The modification is that the optimization is performed with the additional condition that the local velocities are equal at each selected node in the location grid for the
current placement. The final estimate of the layer velocity is calculated as the median velocity obtained at different arrangements of EP and RP.

Figure 4. Approximation of the second boundary.

Estimates of all layer velocities, produced in this example for two arrangements, and their absolute errors are as follows: \( V_1 = 2000.85 \text{ m/sec}, \Delta V_1 = 0.86 \text{ m/sec}; \) \( V_2 = 2208.95 \text{ m/sec}, \Delta V_2 = 8.95 \text{ m/sec}; \) \( V_3 = 2546.34 \text{ m/sec}, \Delta V_3 = 46.34 \text{ m/sec}; \) \( V_4 = 2686.96 \text{ m/sec}, \Delta V_4 = -13.04 \text{ m/sec}. \)

With a larger number of arrangements, the error in estimating stratum velocities can be reduced by calculating their average value for different arrangements.

4. Summary
The article describes a method for consistent assessment of propagation’s layer velocities of seismic waves propagation reflected from several model’s boundaries of the geological environment under study. The method is based on the technology of seismic imaging, which uses DKP solutions for all reflecting boundaries. The technology locates the reflection pulses’ sources from the boundaries of the deep section layers and restores the kinematic parameters of the layers through them.

Figure 5. Ray pattern for determining the fourth layer velocity.

The obtained errors of layer velocities estimate for the given model’s example of the geological environment under study do not exceed 2%.

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