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GEOINFORMATIONAL TECHNOLOGY FOR ESTIMATING THE VELOCITY CHARACTERISTICS OF THE MEDIUM

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Abstract — The paper describes a heuristic approach to determining the local velocities of seismic waves in complex mediums. Based on the results of vibration seismic sounding along two profiles of the volcanic zone of the mud volcano Mount Karabetova, a picture of the distribution of local P-wave velocities was obtained. The results obtained are consistent with the data on the geological structure of the considered area.

Keywords — complex medium; local velocities; seismic waves; inverse problem of geophysics.

INTRODUCTION

One of the important issues in solving inverse problems in seismology related to the determination of the geographic and energy characteristics of a source is obtaining a priori information on the propagation velocities of seismic waves. Along with other factors such as the levels of external noise, the geometry of the placement of the recording receivers, etc., the completeness of the availability of information about the speed characteristics determines the accuracy of solving the inverse problem. Obtaining such information is sharply complicated in relation to media with a pronounced heterogeneity of the structure. This is particularly the case for mediums in areas of volcanic edifices, including mud volcanoes. Consideration of the problem of clarifying the velocity characteristics of the medium with the presence of heterogeneity of its structure on the example of the volcanic zone of the mud volcano Mount Karabetova (Taman mud volcanic province) [1, p. 178–185] defines the content of this work.

PROBLEM STATEMENT

The aim of this work is to construct a numerical model of time-travel curves of local primary wave, typical for the area of mud volcanoes, based on the experimentally obtained arrival times of waves from vibration sources. On their basis, it is possible to construct the velocity characteristics of the medium and take into account the elasticity of the medium in the volcano zone.

The problem of estimating unknown local velocities of seismic waves in an inhomogeneous medium is reduced to solving a nonlinear system of conditional equations:

$$\vec{t} = \vec{\eta}(X,\theta) + \vec{\varepsilon}\ , \qquad (1)$$

where $\vec{t} = (t_1, t_2, \ldots, t_N)$ is the vector of seismic wave arrival times, $\vec{\eta}(X,\theta)$ is the N-dimensional vector of the calculated travel times (theoretical time-travel curve) or the regression function, $\vec{\varepsilon} = (\varepsilon_1, \ldots, \varepsilon_N)^T$ is the error vector, $\vec{\theta} = \left[\left(x_i^*, y_i^* \right), \vec{V}(\vec{v}) \right]^T$, where *($x_i^*$, y_i^*)* — are the coordinates of the radiation points (i = 1,2,…M is the number of radiation points), $\vec{V}$ is the vector of the average values of the velocities of seismic waves in the medium, $\vec{v}$ is the vector of local velocities of seismic waves; $X = (\vec{x}_1, \vec{x}_2, \ldots, \vec{x}_N)$ is the matrix of receivers coordinates, N is the number of receivers. With known *(x_i^*, y_i^*)* the local seismic wave velocities $\vec{v}$ are used as the estimated parameters.

In estimating the parameters, information about the distribution of errors $\varepsilon_i = t_i(\vec{x}_i, \vec{\theta}) - \eta(\vec{x}_i, \vec{\theta})$ is used. In what follows, we will assume that ε_i are mutually independent random variables having a distribution with zero mean and given variances: $E\varepsilon_i = 0$, $E\varepsilon_i \varepsilon_j = \sigma_i^2 \delta_{ij}$, $\sigma_i = \sigma(\vec{x}_i)$, δ_{ij} is the Kronecker symbol, $i = 1, 2, \ldots, N$. In cases of difficulties with setting the variances, they are taken to be equal and an unbiased estimate of the observation variance with a unit weight is obtained as the problem is solved.

The solution of equation (1) is reduced to the solution of the inverse problem of geophysics [2–5]. In this case, the accuracy of the solution depends, first of all, on the errors in estimating the time vector $\vec{t} = (t_1, t_2, \ldots, t_N)$, the residuals $\vec{\varepsilon} = (\varepsilon_1, \ldots, \varepsilon_N)^T$, and choosing the geometry of the placement of receivers on the Earth's surface.

Rigorous methods for solving equation (1) are based on minimizing the residual between the experimental and theoretical time-travel curves in (1) by the least squares:

$$\vec{\theta} = \arg\min_{\vec{\theta} \in \Omega} Q(\vec{\theta}), \qquad Q(\vec{\theta}) = \sum_{i=1}^{N} \sigma_i^{-2} (t_i - \eta(\vec{x}_i, \vec{\theta}))^2 \tag{2}$$

There are well-known rigorous methods for solving (2) based on the multidimensional iterative Gauss-Newton method, generalized inversion based on singular value decomposition (SVD) [5,6], the adaptive Kaczmarz method (Algebraic Reconstruction Technique) [7], etc. One of the examples of applying the SVD method to refine the velocity characteristics of the medium using borehole explosions is the work [8].

At the same time, the use of such methods encounters computational difficulties in solving the optimization problem (2) due to the large dimension of the parameters in the form of wave arrival times $\vec{t} = (t_1, t_2, \ldots, t_N)$ in the problems of monitoring heterogeneous zones. In this situation, solution simplification can be achieved by using a heuristic algorithm while maintaining the acceptable accuracy of the solution.

SOLUTION OF THE PROBLEM

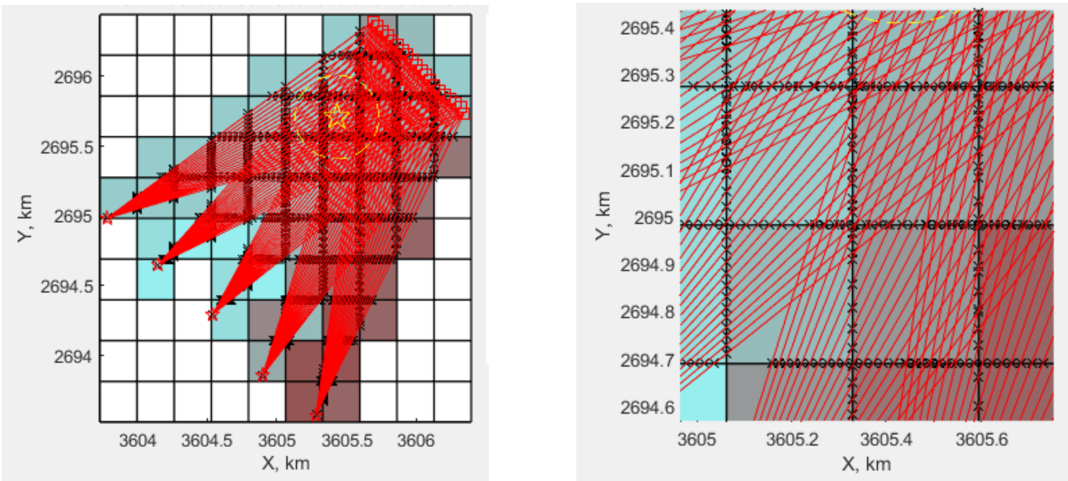
As a method for solving problem (1), an approach is proposed for determining the velocity characteristics of complex media based on dividing the studied area of the medium into sections in which the local velocities of seismic waves are calculated. The equation for determining the average weighted seismic wave velocity $\vec{v}$ for each k-th section of the profile (on the plane) is expressed as follows [9]:

$$\vec{v}_k = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} \vec{V}_{ij} \cdot \frac{L_{ijk}}{L_{ij}}}{\sum_{i=1}^{N} \sum_{j=1}^{M} \frac{L_{ijk}}{L_{ij}}} \tag{3}$$

Where $\vec{V}_{ij}$ is the average velocity of the seismic wave from the seismic source i to the receiver j, L_{ij} is the distance traveled by the seismic wave from the seismic source i to the receiver

j, L_{ijk} is the distance traveled by the seismic wave from the seismic source i to the receiver j in the k-th section of the profile (at the k-th node mesh).

Fig. 1 explains the methodology for determining the weighted average seismic wave velocity. As can be seen from the figure, the Earth's surface is divided into one hundred sections, for which it is necessary to find the velocity values, where k is the section number. There are 20 receivers (marked with diamonds) and five seismic sources (marked with stars) on the Earth's surface.



a) b)

Fig. 1 a) Subdivision of the day surface in the volcano area to determine the weighted average seismic wave velocity for the selected area. The points of sources T1-T5, points of installation of receivers 1,2, ... 20 are presented. The area of the Mount Karabetova mud volcano is highlighted in yellow. b) The same area on an enlarged scale for a visual representation of the distribution of the front of propagation of seismic waves.

The following features of the algorithm follow:

• the longer the path of the seismic wave, the greater its influence on the accuracy of determining the weighted average wave velocity in general and for a specific area;

• the fewer “source-receiver” lines cross the grid section, the less reliably the velocity will be determined for it.

• the choice of the shape of the mesh section affects the accuracy of approximation to the velocity estimate on it, since the velocity is influenced by the length of the “source-receiver” line segments.

• this method works under the assumption that the wave path is straight from the source to the receiver.

Estimating the accuracy of the algorithm is reduced to comparing the theoretical time-travel curve from formula (1) with the vector of seismic wave arrival times obtained in the experiment. Denote the theoretical time-travel curve as $\vec{t}^{\,*}$:

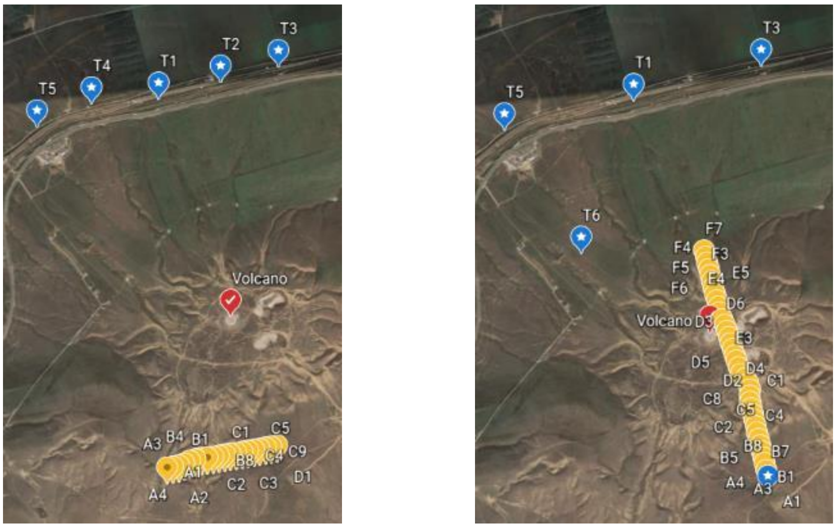
$$\vec{\eta}(X,\theta) = \vec{t}^{\,*} . \qquad (4)$$

Each element of the theoretical time-travel vector is calculated by the formula:

$$\vec{t}_i^{\,*} = \sum_{k=1}^{L} \frac{L_{ijk}}{\vec{v}_k} . \qquad (5)$$

RESULTS AND DISCUSSION

The map of the area of the Mount Karabetova mud volcano in experiments on its vibration seismic sounding along profiles I and II is shown in Fig. 2.

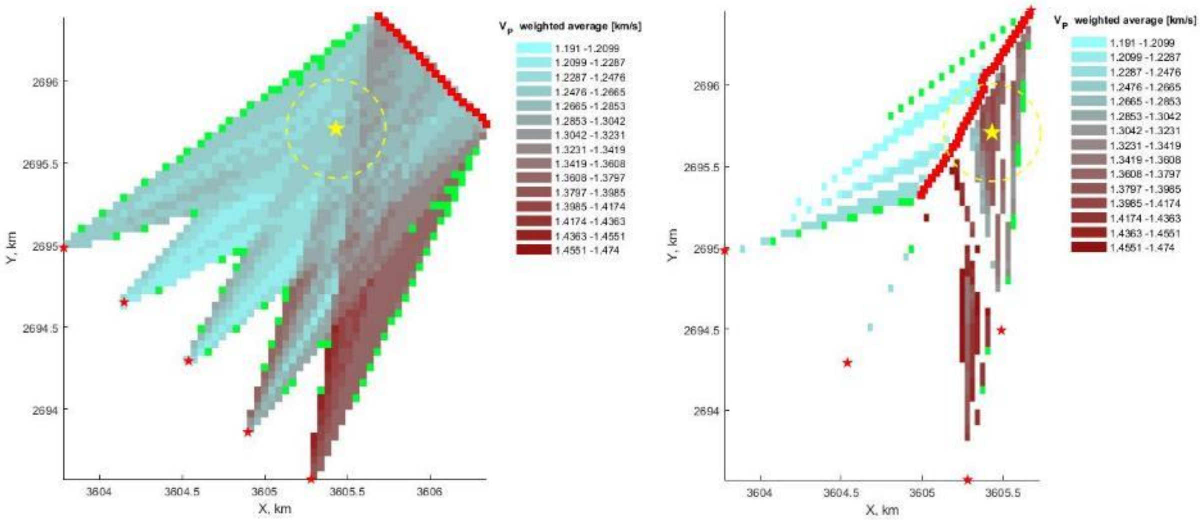


a) b)

Fig. 2 Map of the area of the Mount Karabetova mud volcano in experiments on its vibration seismic sounding: a — on profile I, b — on profile II. The position of the receivers is indicated by yellow flags, seismic sources — by blue flags, the volcano area — by a red flag.

To determine the local velocities of P-waves along the sections of each profile, a square grid with a uniform number of nodes (60x60) along both axes of the Cartesian plane was chosen. The grid spacing for profile I was 42.7 m along the *x* axis and 47 m along the *y* axis, and for profile II, 31.5 m and 48.1 m, respectively. The results of determining the local velocities for both profiles are shown in Fig. 3. After the transformation of geodetic coordinates into Cartesian [10], the map of the location of sources and receivers turned almost 180 degrees counterclockwise. However, this does not interfere with the interpretation of the data. The range of local velocities for both profiles is from 1.191 to 1.474 km / sec. Fig. 3 shows that in the right area for both profiles, higher velocities prevail, which may be caused by the presence of an anticlinal flexure in this area, which is characterized by a denser geological structure [11, p. 231].

The estimation of the algorithm accuracy according to formula (5) for profile I is shown in Fig. 4. It can be seen from the figure that for the T4 and T5 sources, the error in determining the P-wave arrival times is higher in the region of 11-th, 15-20-th receivers. This may be due to the fact that local velocities in the region of the T4 and T5 sources are higher than in the rest of the region. Also, the contribution of each of the sources to the determination of local velocities is significant in the region close to the receivers due to the large number of crossings of the "source-receiver" lines in this region.



a) b)

Fig. 3 Distribution of local P-wave velocities on the day surface in the volcano area for profiles: a) I, b) II. Red stars indicate the position of seismic sources, red diamonds — the position of receivers. The area of the Mount Karabetova mud volcano is highlighted in yellow. Areas are highlighted in green, where local velocities are calculated only along one “source-receiver” line.

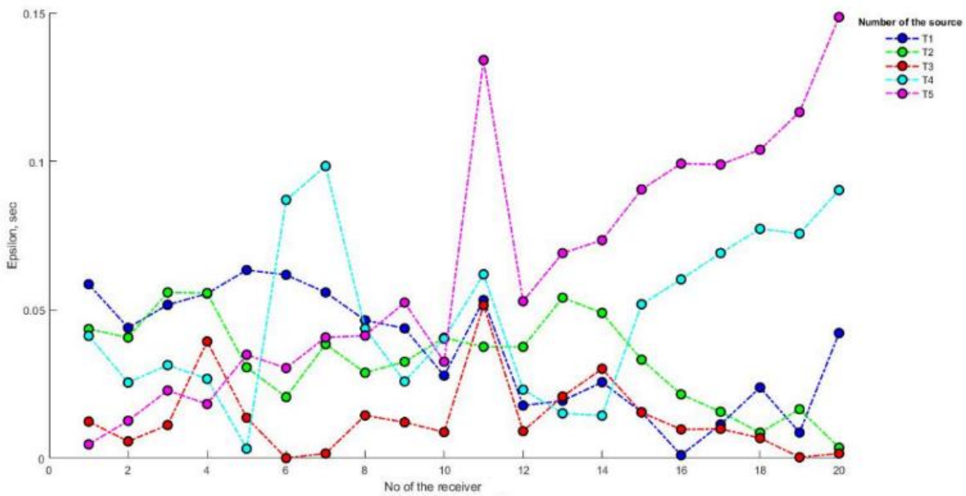


Fig. 4 Distribution of errors in calculating the theoretical time-travel curve for all seismic sources for receivers No 1-20 along profile I

CONCLUSION

This paper presents a heuristic approach to constructing local velocity characteristics of complex mediums, such as areas of mud volcanoes, based on experimentally obtained vibration seismic sounding data. The developed algorithm is tested on the data on the experimentally obtained arrival times of waves from vibration sources of the mud volcano Mount Karabetova along two profiles. It is shown that the obtained results of the distribution of local velocities are consistent with the data on the geological structure of the considered area.

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CONSTRUCTION OF A STRENGTH MODEL OF A STRAPDOWN INERTIAL BLOCK OF A SPACE ORBITER

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Annotation – Increasingly stringent requirements are imposed on modern onboard spacecraft equipment in terms of functionality, mass and size parameters, reliability and manufacturability. The cause of this demands is the acceleration of scientific and technological progress, the growing ambitions of mankind to explore outer space. The current trend is to miniaturize electronic devices maintaining the output characteristics, hence the need to modernize the design and technology of both the spacecrafts and the onboard equipment.

In this article the development of a strength model of a strapdown inertial unit, an integral part of a strapdown inertial navigation system is presented.

At the design stage we performed calculations to determine the system strength. All calculations were performed in the SolidWorks CAD environment. The two cases: linear acceleration and impact effect were taken into consideration.