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METHODS OF MODELING VELOCITY CHARACTERISTICS OF THE GEOLOGICAL ENVIRONMENT ON THE BASIS OF THE THREE-DIMENSIONAL SEISMIC DATA AND WELL DATA

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МЕТОДИ МОДЕЛЮВАННЯ ШВИДКІСНИХ ВЛАСТИВОСТЕЙ ГЕОЛОГІЧНОГО СЕРЕДОВИЩА НА ОСНОВІ ДАНИХ ОБ'ЄМНОЇ СЕЙСМОРОЗВІДКИ Й СВЕРДЛОВИННИХ ДАНИХ

Purpose. Development of geological and geophysical models based on cut logging and seismic data using the latest technology processing, interpretation and integrated analysis of the available data. This will help to improve existing velocity models, and to avoid mistakes when creating new ones.

Methodology. Specialized algorithms of migrational transformation of seismic data, modern methods of complex analysis of geological and geophysical data, building technologies of comprehensive velocity models of the geological environment were used. Correlation and features of ways to determine the velocity model in the case of biaxial and triaxial ellipsoids of radial velocity, as well as for isotropic model environment are considered.

Findings. Methods of constructing velocity models, which will improve the results of the interpretation of geological and geophysical data are proposed. While analyzing seismic data particular attention was paid to anisotropy consideration. Linking borehole data, which have higher accuracy and resolution, with the three-dimensional seismic data, and the consideration of anisotropy help to get a velocity model with high reliability. Subsequently, the proposed methods for constructing velocity models can be used to simplify and optimize the process of constructing geological and geophysical models.

Originality. We propose new ways of getting different values of velocity spectra. Possibilities of determination of the azimuthal velocity divergence in their three-dimensional spectra are considered.

Practical value. Presented methods for constructing velocity models can be used to optimize the process of construction of geological and geophysical models. Linking well data, which have high accuracy and resolution, with the data of the three-dimensional seismic and accounting anisotropy will help to get a velocity model with a high degree of accuracy.

Keywords: *velocity model, ellipsoid, ray velocity, anisotropy, vertical seismic profile*

Introduction. Success of geological exploration work essentially depends on the accurate understanding of the velocity properties of geological rocks. Unfortunately, today our abilities in instrumental measuring of acoustic behavior of rocks are limited by laboratory measurements of drill samples and well-logging measurements. Namely, obtained results are significantly one-dimensional, if we are talking about geological area as a whole; it introduces some uncertainty into the process of forecasting velocity characteristics of three-dimensional environment.

In order to build reliable seismic images, so to say to obtain the main result of seismic exploration work it is crucially important to determine distribution of seismic

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velocities in geological media. Special feature of anisotropic media, which can approximate most of geological media, is the incorrectness of determining vertical semi axes of ray velocity indicatrix based on acquired onshore (and offshore) seismic data. This is the reason for difficulties in interpretation of the velocity analysis results using onshore seismic data both for isotropic and anisotropic media [1].

Velocity model of the geologic environment is approximated during seismic processing and migration of seismic data, allowing achieving the desired result with some approach. Subsequently, it is widely used for deep transformations of the three-dimensional geological models. And the price of uncertainty, error in determining the velocity characteristics of the environment can be very high including nonpenetrating wells, errors in determining the lithology and, consequently, incorrectly developed method of drilling, etc. The cost of such errors is very high both in money and in time equivalents.

One of the effective ways to approximate the velocity model of the geological environment and is typical for sedimentary basins, is to describe velocity model using elliptical indicatrix of ray velocity. A characteristic feature of this velocity model is incorrect data registered in the XOY plane. This is what often causes difficulties in interpretation of the velocity analysis results using surface seismic data in the case of isotropic and anisotropic models of environment.

Regarding this, in this paper the relationship and features of the ways to determine the velocity models in the case of biaxial ellipsoids and tiaxial ellipsoid of ray velocity, for isotropic model of the environment is considered. New ways to get different in value velocity spectrum are proposed. The possibilities of determining azimuthal velocity divergence in their three-dimensional spectra are considered.

Methods and research facilities. For planar reflecting boundary errors in determining the vertical velocity do not change the shape of reflecting boundary on seismic images. Only its position in space is changed. Equation of the reflecting boundary on seismic images has the form [1]

$$
\begin{gathered}
x\frac{-2x_{s_1}+2x_{d_1}}{v_x{}^2}+\\
+\frac{x_{s_1}{}^2-x_{d_1}{}^2}{v_x{}^2}+y\frac{-2y_{s_1}+2x_{d_1}}{v_y{}^2}+\\
+\frac{y_{s_1}{}^2-x_{d_1}{}^2}{v_y{}^2}+z\frac{(-2z_{s_1}+2z_{d_2})z_{d_1}{}^2}{v_z{}^2 z_{d_2}{}^2}+\\
+\frac{(z_{s_1}{}^2-z_{d_1}{}^2)z_{d_1}{}^2}{v_z{}^2 z_{d_2}{}^2}=0,
\end{gathered}
\qquad (1)
$$

where v_x, v_y, v_z are velocities of seismic waves in the direction of x, y, z respectively; s_1, d_1 are symbols that define the real and imaginary sources of seismic waves, respectively; d_2 is the symbol that identifies false imaginary source of seismic wave.

False vertical velocity in the above equation indicates the expression $\frac{z_{d_2}}{z_{d_1}}v_z$. If we formally assume that the seismic receivers are located in the XOZ plane, then errors in determining the velocity will lead to changes in the position of a plane reflecting boundary on seismic image. In turn, the position of the seismic receivers in the YOZ plane allows changing the velocity v_x with the appropriate change of the position of the planar reflecting boundary on seismic image. In the latter two cases, the false velocity is determined by the following expressions

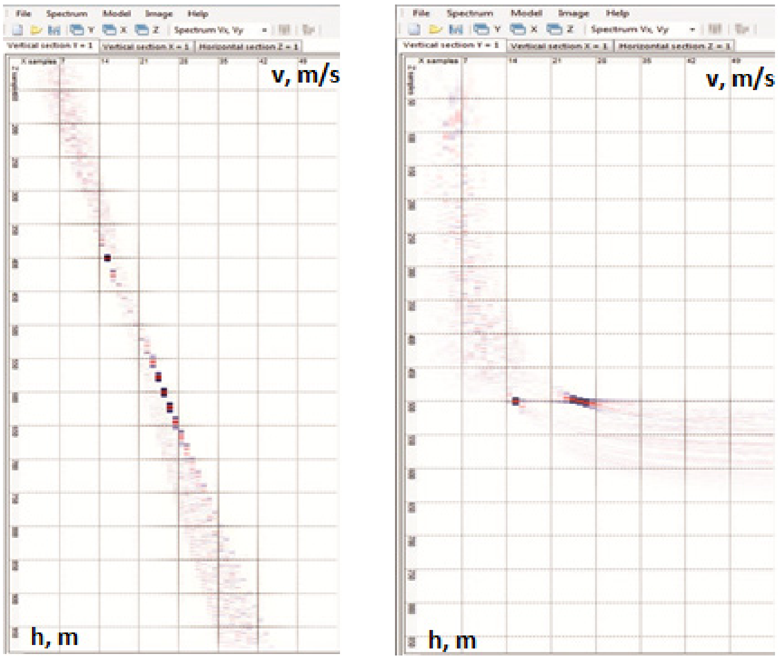
$$\frac{y_{d_2}}{y_{d_1}}v_y;\quad \frac{x_{d_1}}{x_{d_1}}v_x.$$

Let us consider the possibility of determining the velocity model with elliptical anisotropy using direct conversion of depth point gather into the seismic image of geological environment. In the simplest case, isotropic environment, relative to the velocity of seismic waves, which is a particular case of elliptically anisotropic medium, range of speeds has a traditional appearance and is shown in Fig. 1, *a*. Interval sampling range on the horizontal axis, which determines the velocity, is 25 m/s, and the vertical axis, which determines the depth, is 5 m. The range meets the environment, which includes two reflective boundaries with depths of 2000 and 3000 m. Velocity to borders level 2000 and 3000 m/s, respectively. Resolution of the velocity analysis decreases with depth, it is clearly seen in Fig. 1.

It is important to note that the definition of the spatial distribution of the values of the seismic waves velocity in their spectra, supposing the isotropic medium model of sedimentary basins, in most cases gives a reliable distribution rates of v_x or v_y velocities. This is due to the fact that it is the anisotropic model of velocity distribution of seismic waves not the isotropic one which coressponds to the real-layered geological environment. With this definition of velocities, the v_z velocities are overstated by the amount of about 10 %. This leads to a corresponding increase in depth of reflecting boundaries on seismic images.

For an anisotropic medium, velocity model of which is described with the biaxial ellipsoid, thereby velocities v_{hor} and v_z getting a spectrum is a little complicated. Given that the change of the velocity v_z will lead only to the moving of reflecting boundary, then it is impractical to enter an additional third coordinate in the range of speeds. When obtaining the spectrum the values of velocities can be fixed by giving it some typical average.

Fig. 1, *b* shows the range of velocities obtained for the elliptically anisotropic medium as a biaxial ellipsoid. To calculate the value of the spectrum the v_z velocity is used, it is equal to 2500 m/s. This choice of v_z leads to the change of depth of the first reflecting boundariy in the spectrum from 2000 to 2500 m. This increase is due



a *b*

Fig. 1. Examples of velocity spectrum used for direct conversion of common depth point seismograms in the seismic image of geological environment (a) isotropic model of the environment, and (b) elliptically anisotropic model of the environment with indicatrix of ray velocity as a biaxial ellipsoid (horizontal axis determines the speed, vertical — depth)

to the positive mistake in choosing v_z velocity, which is 500 m/s. At the same time, the depth of the second boundary of the spectrum changed from 3000 to 2500 m. In this case, the reduction of the depth is caused by the negative mistake in the choice of v_z velocity, which is 500 m/s.

Calculation of the velocity spectrum in case of triaxial ellipsoid requires the use of three-dimensional velocity spectrum. Let us make some changes in the velocity model of the environment. We define the following values of semiaxes of elliptical indicatrix of ray velocity: for the first reflecting boundary – $v_x = 2200$ m/s, $v_y = 2100$ m/s, $v_z = 2000$ m/s; for the second reflecting boundary – $v_x = 2750$ m/s, $v_y = 3000$ m/s, $v_z = 2500$ m/s. Fig. 2 shows the different crossings of the three-dimensional range of velocities. Two orthogonal horizontal axes of the spectrum determine velocities v_x and v_y, and the vertical axis determines the depth. Complicated work with this spectrum is due to the need to analyze its individual two-dimensional sections. Fig. 2, *a* shows a vertical section of the spectrum, which corresponds to a false velocity in any of the two reflecting boundaries. At this intersection there are no criteria for choosing any value of v_x or v_y velocities.

Fig. 2, *b* shows a vertical section of the spectrum for a constant velocity $v_y = 2100$ m/s. The horizontal axis intersection determines the v_x velocity. The correct velocity $v_x = 2200$ m/s corresponds to the maximum value of the amplitude of wave on the spectrum. Position of the reflecting boundary has changed from 2000 to 2500 m due to the positive mistake when choosing v_z velocity, which is 500 m/s.

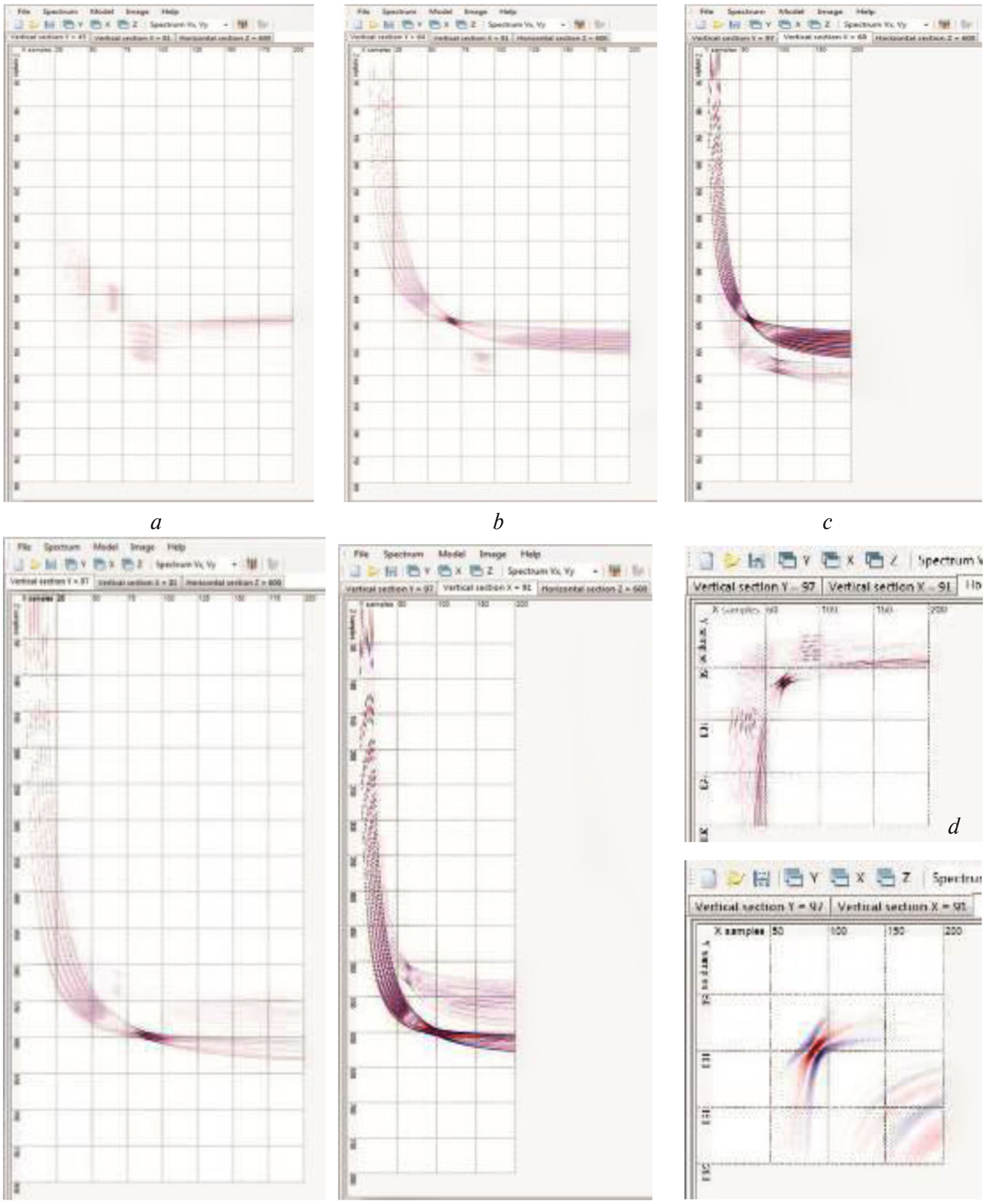
Fig. 2, *c* shows a vertical section of the spectrum for a constant speed $v_x = 2200$ m/s. The horizontal axis intersection determines the v_y velocity. The correct speed $v_y = 2100$ m/s corresponds to the maximum value of the amplitude of wave on the spectrum. As in the previous section, reflecting the border is shifted 500 m towards the increasing depth.

Fig. 2, *d* shows the horizontal cross section range of velocities. In this case, the horizontal axis corresponds to the v_x velocity and the vertical one corresponds to v_y. The matching of velocity spectrum with the velocities in the environment is determined by the maximum amplitude of the wave at the point $v_x = 2200$ m/s, $v_y = 2100$ m/s.

Figs. 2, *e, f, g* shows three sections, which pass through the coincident point of velocities for the second reflecting boundary. The point has the following coordinates on the velocity spectrum $v_x = 2750$ m/s, $v_y = 3000$ m/s, z = 3000 m. The matching of z coordinates with the true depth of reflecting boundaries coincidence rate is explained by matching of velocity v_z in the geological environment with the velocity $v_z = 2500$ m/s, which was used to calculate the three-dimensional range of speeds.

Building a high-velocity models based on the borehole data. The main source of borehole data on the distribution of rock velocities are the results of vertical seismic profiling (VSP) [3]. The velocity characteristics of the subsurface are determined mainly by the graphs of the P- and S-waves of the longitudinal VSP. Transverse waves are excited by a directed source. In cases where such a source cannot be realized, the values of the velocity of transverse waves can be determined by the graphs of the exchange of incident and reflected waves.

It is also worth noting that MSP is the most effective method for determining the relationship between veloc-



a *b* *c* *d* *e* *f* *g*

Fig. 2. Crossing of the three-dimensional velocity spectrum for elliptically anisotropic model of the environment with the indicatrix of ray velocity as a triaxial ellipsoid:

a – vertical section, which does not contain velocity coincidence points; b – a vertical section in direction v_x *that includes a match point of velocities for the first reflecting boundary; c – vertical section in direction* v_y *that includes a match point of velocities for the first reflecting boundary; d – horizontal section with the coordinate axes* v_x *and* v_y*, containing a match point of reflecting boundary; e – a vertical section in direction* v_x *that includes a match point of velocities for the second reflecting boundary; f – a vertical section in direction* v_y *that includes a match point of velocities for the second reflecting boundary; g – horizontal section with the coordinate axes* v_x *and* v_y *containing a match point of velocities for the second reflecting boundary*

ity anisotropy and the structure of the medium, moreover the anisotropic properties of the medium can be detected both by direct determination of velocities and indirectly.

When conducting VSP the first arrivals, that is, direct waves from a source located on the surface of the earth (or in a shallow blast hole), are recorded as well as subsequent arrivals, which belong to reflected, multireflected and other waves. This provides more accurate determination of the velocity of seismic waves in the environment around the well profile, as well as studying the structure of the observed wave fields.

Defining the first arrivals of incident waves is one of the specific procedures for data processing of the VSP. One of the commonly accepted is the correlation method for determining the time increment between seismographs and determining the absolute time of “failure” in the average recording. Another approach is to trace the characteristic points of the first half-period, which are the points of inflection and the points of the maximum gradient, the extremums of the function and its first derivatives [3].

The data on first arrivals can be converted to velocity parameters of the environment – medium, reservoir and interval velocities.

Taking into account the fact that VSP studies are conducted with different equipment and with different methods, it is necessary to convert the data to a single level of reduction (mean sea level or 150 m. It is a standard adopted in geological expeditions operating in the Dnipro-Donetsk Basin).

At the first stage vertical travel time graphs are reduced to an absolute mark and editing of the clearly inaccurate values of wellshot is conducted.

At the second phase prepared travel time graph is converted into travel time with an equal step — in case its step is 20 m or more, the initial step of the travel time graph is assumed to be 20 m. If the source travel time graph has a step of 10–15 meters and more, the step of output is assumed to be 10 m.

And on the basis of the data the main velocity parameters of the environment are calculated.

Average and interval velocities are based on conventional petrophysical dependencies. Average velocity is

$$v_{p\_av} = \frac{H}{T_p}, \qquad (2)$$

where v_{p_av} is the average rate of longitudinal (v_p) wave; H is a vertical depth of the level of harmonization; T_p is vertical travel time of a longitudinal wave.

Interval velocity is

$$v_{\text{int}} = \frac{\Delta H}{\Delta T_p}, \qquad (3)$$

where v_{int} is the interval velocity of a longitudinal wave; ΔH is base differentiation in depth; ΔT_p is vertical travel time of a longitudinal wave. The calculation of interval velocity models by traditional methods (choice of break point on the vertical travel time) is the most subjective. The proposed method minimizes the influence of subjective factors. To construct reservoir model interval velocities are used rather than vertical travel time graphs; according to algorithms adopted in industrial geophysics, the velocities are split into layers. Later, the following relationship is used

$$v_p = \frac{\Delta H}{\Delta T_p}, \qquad (4)$$

where v_p is interval velocity; ΔH is power of the layer; ΔT_p is vertical travel time of a longitudinal wave.

Based on the calculated data of the layer velocities the direct problem is solved – calculation of vertical travel time graph, which is compared with the actual travel time graph. In case of the quality matching the process ends, in the opposite case, the model is adjusted by solving the inverse problem using the method of the reduced graph with repeated both visual and statistical control.

Conclusions. In this work methods of creating velocity models of the geological environment on the basis of the three-dimensional seismic and borehole data are considered. While analyzing seismic data, special consideration was given to the anisotropy. Linking borehole data, which have higher accuracy and resolution, with the three-dimensional seismic data, and the consideration of anisotropy help to get a velocity model with high reliability. Subsequently, the proposed methods for constructing velocity models can be used to simplify and optimize the process of constructing geological and geophysical models.

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Мета. Розробка геолого-геофізичної моделі розрізу за допомогою каротажних і сейсмічних даних із використанням новітніх технологій обробки, інтерпретації й комплексного аналізу наявних даних. Це дасть змогу покращити вже існуючі швидкісні моделі, та не робити помилки при створенні нових.

Методика. Спеціалізовані алгоритми міграційних перетворень сейсмічних даних, сучасні методи комплексного аналізу геолого-геофізичних даних, технології побудови комплексних швидкісних моделей геологічного середовища. Розглядається взаємозв’язок і особливості способів визначення швидкісних моделей у випадках двовісного та тривісного еліпсоїдів променевої швидкості, а також для ізотропної моделі середовища.

Результати. Пропонуються способи побудови швидкісних моделей, що дозволять покращити результати інтерпретації геолого-геофізичних матеріалів. При аналізі даних сейсморозвідки особлива увага була приділена врахуванню анізотропії. Ув’язка свердловинних даних, що мають вищу точність і роздільну здатність, із даними площинної сейсморозвідки, і врахування анізотропії допомагають отримати модель швидкостей з високим рівнем достовірності. У подальшому запропоновані способи побудови швидкісних моделей можуть бути використанні для спрощення та оптимізації процесу побудови геолого-геофізичних моделей.

Наукова новизна. Пропонуються нові способи отримання різних за значенням спектрів швидкостей. Розглядаються можливості визначення азимутальної дивергенції швидкостей за їхніми тривимірними спектрами.

Практична значимість. Представлені способи побудови швидкісних моделей можуть бути використані для оптимізації процесу побудови геолого-геофізичних моделей. Ув'язка свердловинних даних, що мають вищу точність і роздільну здатність, із даними площинної сейсморозвідки і врахуванням анізотропії допомагають отримати модель швидкостей з високим рівнем достовірності.

Ключові слова: *швидкісна модель, еліпсоїд, променеві швидкості, анізотропія, вертикальне сейсмічне профілювання*

Цель. Разработка геолого-геофизической модели разреза с помощью каротажных и сейсмических данных с использованием новейших технологий обработки, интерпретации и комплексного анализа имеющихся данных. Это позволит улучшить уже существующие скоростные модели, и не делать ошибки при создании новых.

Методика. Специализированные алгоритмы миграционных преобразований сейсмических данных, современные методы комплексного анализа геолого-геофизических данных, технологии построения комплексных скоростных моделей геологической среды. Рассматривается взаимосвязь и особенности способов определения скоростных моделей в случаях двухосного и трехосного эллипсоидов лучевой скорости, а также для изотропной модели среды.

Результаты. Предлагаются способы построения скоростных моделей, которые позволят улучшить результаты интерпретации геолого-геофизических материалов. При анализе данных сейсморазведки особое внимание было уделено учету анизотропии. Увязка скважинных данных, которые имеют высшую точность и разрешающую способность, с данными плоскостной сейсморазведки, и учет анизотропии помогают получить модель скоростей с высоким уровнем достоверности. В дальнейшем предложенные способы построения скоростных моделей могут быть использованы для упрощения и оптимизации процесса построения геолого-геофизических моделей.

Научная новизна. Предлагаются новые способы получения различных по значению спектров скоростей. Рассматриваются возможности определения азимутальной дивергенции скоростей по их трехмерным спектрам.

Практическая значимость. Представленные способы построения скоростных моделей могут быть использованы для оптимизации процесса построения геолого-геофизических моделей. Увязка скважинных данных, которые имеют высокую точность и разрешающую способность, с данным площадной сейсморазведки и учетом анизотропии помогают получить модель скоростей с высокой степенью достоверности.

Ключевые слова: *скоростная модель, эллипсоид, лучевые скорости, анизотропия, вертикальное сейсмическое профилирование*

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