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Satbayev University

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ИЗВЕСТИЯ

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SOLUTION OF THE GRAVITY EXPLORATION DIRECT PROBLEM BY THE SIMULATED ANNEALING METHOD FOR DATA INTERPRETATION OF GRAVITY MONITORING OF THE SUBSOIL CONDITIONS

Abstract. The long-term development of hydrocarbon reservoirs (HCR) in the geological environment, complex deformation processes occur. Gravity monitoring is carried out to evaluate the possible geodynamic risk and negative consequences from HCR. As a result, the interrelationships of the continuously changing field-geological situation (changes in production volumes, changes in reservoir pressure, processes of fluid injection into productive formations) are investigated. The main tool for solving the gravity inversion when determining areas of increased industrial hazard is the solution of the gravity direct problem. In these studies, proceeding from a given initial approximation of the environment, the problem is realized through successive approximations. To assess such distributions, the authors of the article recommend using the simulated annealing technique within the framework of stochastic optimization. It is aimed at fitting the optimal parameters of the medium provided that a minimal residual of the gravity field values occurs.

The approach is implemented using three simple mathematical models of the geological medium such as horizontal prism, homogeneous sphere, and vertical ledge. This technique allows fitting the media values simultaneously by a pair of its parameters. The operation of the algorithm is described and the simulation results are provided. The results showed acceptable accuracy of the algorithm for solving the direct gravity problem by the proposed method. The simulated annealing technique made it possible to increase the reliability of the HCR model while reduce the time for the analysis of the gravity field.

Key words: gravity direct problem, simulated annealing approach, gravity variations, gravity monitoring, hydrocarbon field.

1. Introduction. Complex geodynamic processes of a natural and technogenic nature always accompany the *forced deriving* of matter in the hydrocarbon reservoirs (HCR) in *natural mode*. These processes are especially acute in the HCR located within active faults. The reason for their activation may be *local* changes in the tectonic environment and the *geotechnical* effects (variations in reservoir pressure). They, in turn, are a consequence of the high modern tectonic activity of faults and the rock breaking disruptions [1]. Besides the local tectonic geodynamic phenomena (developed in various forms) geodynamic events of technogenic genesis during the exploitation of the HCRs are known in many oil and gas bearing basins such as seismic movements, abnormal subsidence of the ground surface, horizontal shifts of rock masses, and formation of the surface cracks. In this regard, the relevance of obtaining prompt and reliable information about the geodynamic state of the developed HCRs is indisputable.

An evaluation of the potential geodynamic risk and the possible negative consequences of a prolonged exploitation of HCRs is impossible without comprehensive geodynamic monitoring of the HCR [2], including the study of reservoir pressure dynamics. An optimal in accuracy and speed preset of methods for evaluation the geodynamic processes combines strain monitoring (levelling, satellite interferometry, InSAR) with gravimetry. The latter method, as an inexpensive, fast and effective method of geophysics, has been successfully used in field development process when assessing the effect of fluid replacement in productive formations, studying reservoir compaction and zones of faults activation, identifying areas of increased industrial and geodynamic hazard, etc. [3]. Work [4] presents an example of a comprehensive assessment of geodynamic processes occurring during the development of HCR based on leveling and satellite observations.

For the successful solution the problems of geodynamic monitoring of the subsoil conditions by gravity measurements, a convenient data processing service (including the filtration, calculation and introduction of the necessary gravity corrections and reductions) as well as the interpretation unit for the calculated gravity variations are required. The main role in this service is assigned to solving the direct problems of gravimetry for various model assumptions on the structure of the studied geological medium [5-7]. Such a solution is the result of successive approximations, based on a pregiven initial approximation of the medium.

The logic of the serial computation algorithm for the direct gravimetry problem solution is simple: we select a certain set of *elementary* approximating bodies with a *simple* given geometry inside a *homogeneous* layered medium. Then we assume that these bodies are contained in a confined layer, which contains the *sources* of the studied gravity anomalies. The direct problem is solved by fitting the optimal parameters to obtain the minimal residual between the measured and calculated gravity values [8].

Traditional methods for solving the direct problems of gravimetry [6] do not meet the requirements for use them in singular conditions. In conditions of singularity, speed of decision making in conditions of confined initial data is crucial. Because of it, factor analysis is no longer effective due to a lack of time and the data. Heuristic models may provide a temporary solution, but we must to review them constantly while new information. Moreover, when you do not have enough basic data to build a hypothesis, and you have to correct them more and more, Bayesian methods are most effective, but with an eye to using machine learning (ML) for quick pattern recognition.

Among probabilistic methods, the so-called genetic algorithms, including the generative adversarial optimization techniques, meet the above criteria. In [8], it was shown that among the set of the genetic algorithms, *the simulated annealing approach* is the most acceptable for our purposes.

The purpose of the study is to demonstrate, using a number of simple mathematical models of the geological medium, the viability of the simulated annealing approach for the *stable* solution of the gravity direct problems.

2. Data acquisition. The realization of the geodynamic monitoring (GDM) of the state of bowels of the Earth in oil and gas fields is an obligatory measure at the development of HCRs. One cycle of measurements per year is enough to accumulate the data, based on which we can determine the presence of deformations in the bowels of a developed HCR [2]. During the gradual extraction of oil, it is replaced by water, which entails a change in the *total density* of the reservoir rocks. This results in the negative dynamics of gravity anomalies, which are recorded by high-precision *gravity monitoring* of the HCR. Its data allows us to prevent quickly the adverse processes in the HCR, providing the subsoil user with the significant retrenchment of supply and costs.

A special GIS GeoM was created [9,10] for storage and processing of the gravity monitoring data. PostgreSQL DBMS, PostGIS, GeoServer were used as free software to create GIS. GIS allows us to import the source files of records from gravimeters, to convert them, to filter the data, to make the necessary corrections, to extract the statistical information, to do the samplings and summary matrices, to average the data and to perform other linear transformations on them. The paper [10] describes the functional modelling of the main business processes for doing gravity monitoring at this HCR, and the implementation of the general subsystems of the mentioned GIS.

Figure 1 shows the DFD model of the “Solving the direct problem of gravity by simulating annealing method” business process. The process consists of the following sub-processes:

– selection of a mathematical model;
– selection of the starting point of the objective function f (x0);
– calculation of a new objective function f (x ');
– generation of a random number α;

– set E = E’;
– calculation of the probability function;
– checking the stopping criterion;
– obtaining the minimal of the gravitational gravity field values.

To perform these processes, you need: processed data of gravimetric measurements, geological and lithological characteristics. At the output, we obtain the calculated value of the gravitational field of the gravity force, the minimum residual, the time of the calculation, the number of performed iterations, the optimal values of the sought parameters.

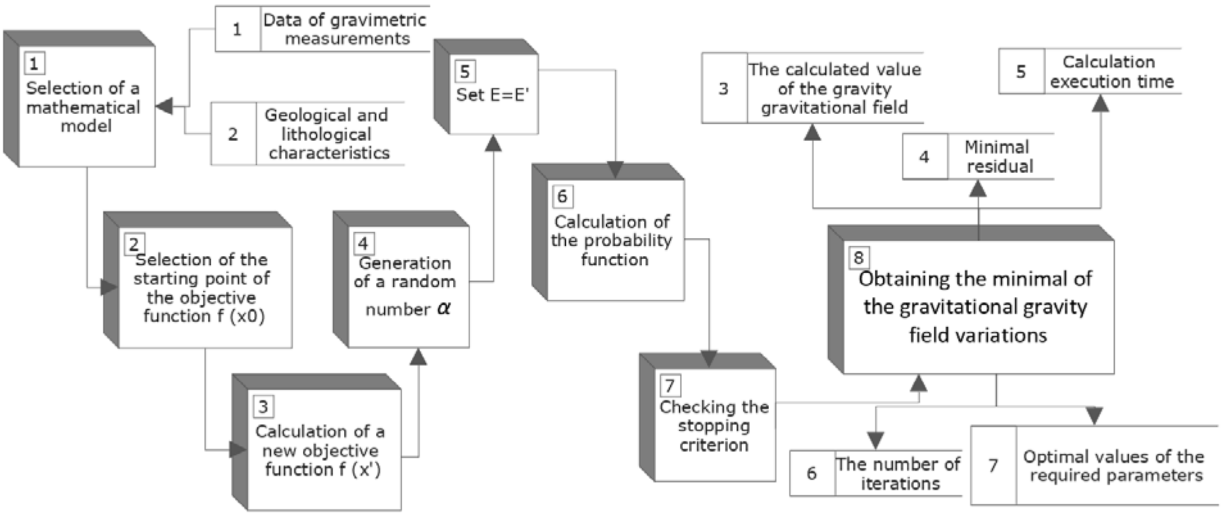


Figure 1 – DFD-model of the “Solving the direct problem of gravity by simulating annealing method” business process

The computational algorithm of this module is realized based on one of the modifications of the simulated annealing technique. Its primary testing on synthetic models was carried out earlier in [11]. In this case, it is necessary to verify the viability of the technique on real field data. For this purpose, the gravity observations made by one of the companies of the Republic of Kazakhstan, which has been engaged in this kind of research for a long time, is involved. The initial data are the digital records of the measurement of gravity variations within the gas-oil field, which is located within the Kzylkoginsky district of the Atyrau region of the Republic of Kazakhstan (it starts operation in 1995).

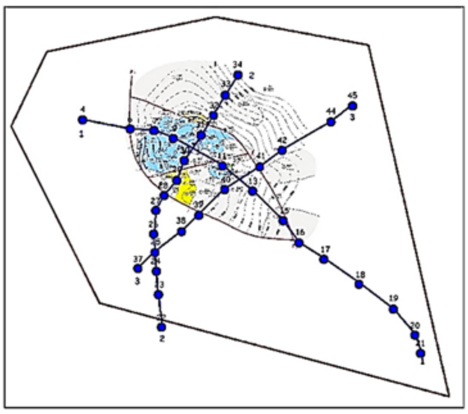


Figure 2 – The layout of points and profiles in the M reservoir

The gravity measurements at the M field are distributed through the long, almost linear profiles that intersect the general structural and tectonic features of the HCR: the arch part, faults, and boreholes pass in close proximity to the geological sections. The observation system with three profiles and 35 measurement points covers the entire territory of the field and the adjacent areas (see figure 2). The profile 1-1 with a length of about 8000 m consists of 14 points, while the profile 2-2 with a length of 1500 m consists of 13 measurement points, and the profile 3-3 that has a length of 3500 m consists of 8 measurement points; the approximate step along the profile is 100 m. At each gravimetric point, several measurements were made with two gravimeters simultaneously, and then the data were averaged to increase the accuracy and the stability of the observations.

The preliminary processing of the data from the catalog (with spatio-temporal reference) included the filtering, averaging, and the calculation of root mean square errors. The correction for the intermediate layer (a Bouguer correction) was calculated by the formula $\delta g_B = -0.0418\sigma_c h$, where σ_c is the average density of the rocks of the intermediate layer (g/cm^3); h is the height of the observation point above the surface of the geoid (m). The obtained Bouguer anomaly Δg_B is the difference between the observed and synthetic gravity field: $\Delta g_B = g_{obs} - \gamma_0 + 0.3086h + \delta g_B$, where g_{obs} is the observed field, γ_0 is the normal value of the acceleration of gravity. The normal gravity was calculated for each profile point according to the formula $\gamma_0 = g_e \cdot (1 + 0.005302 \cdot \sin 2\phi - 0.000007 \cdot \sin^2 2\phi)$, where g_e is the average value of the normal acceleration of gravity at the equator of the Earth, and ϕ is the latitude of the observation point. In calculating the Bouguer anomalies, we took the average density of rocks of the intermediate layer in the core research area of ~ 2.65 g/cm^3.

3. Methods and models. Taking into account *a priori* geological information about the site structure for each specific profile, we solve the direct problem of gravimetry with the least-squares fitting approach for each profile. We solve the problem for various models of the geological medium containing the sources of gravity anomalies in a certain horizontal layer. We chose the fast simulated annealing approach [12,13] as the main solution technique while a compared algorithm is a solution of the gravity direct problem for the Poisson equation by the finite differences technique. To discretize the equation, we chose a “cross-like” difference scheme [14]. Besides, we took the same initial data and a *priori* restrictions for both methods.

Therefore, we tested the simulated annealing algorithm on the example of solving the one-dimensional (by profile) gravity direct problem for three common classes of sources: a horizontal prism (see Section 3.1), a sphere (see Section 3.2), and a vertical ledge (see Section 3.3). A horizontally layered model with a linear change in density inside the anomalous layer is accepted as the initial model of the medium. Outside the layer, we assumed a uniform enclosing medium, which is described by a monotonic density distribution having a constant predefined value. Accordingly, one of three states describes the mathematical model of the studied layer containing the sources of anomalies: a set of horizontal prisms (with different horizontal lengths and densities); a set of spherical bodies (with different radius and depth of the centre of mass); a set of vertical ledges (with different depths and lengths of steps).

In this work the simulation was carried out through the fitting of the objective function, sequentially choosing the location, size, shape, and the density σ of anomalous bodies in the application for calculating the gravity anomalies. The simulation results are presented below.

3.1. Horizontal prism. A horizontal prism as an elementary approximating body within a layer is a special case of a rectangular parallelepiped. At its base lies a regular rectangle, therefore its numerical parameters (length, width, height) we set as the difference of the coordinates of the corresponding points in the Cartesian coordinate system. To calculate the gravity impact of a horizontal prism confined by the planes $x = \xi_1$, $x = \xi_2$, $z = \zeta_1$, $z = \zeta_2$, we use the following expression:

$$U_z(0,0) = G\sigma\begin{bmatrix} \xi_1 \ln\left(\frac{\xi_1^2+\zeta_2^2}{\xi_1^2+\zeta_1^2}\right) - \xi_2 \ln\left(\frac{\xi_2^2+\zeta_2^2}{\xi_2^2+\zeta_1^2}\right) + 2\zeta_2\left(\operatorname{arctg}\left(\frac{\xi_1}{\zeta_2}\right) - \operatorname{arctg}\left(\frac{\xi_2}{\zeta_2}\right)\right) \\ +2\zeta_1\left(\operatorname{arctg}\left(\frac{\xi_2}{\zeta_1}\right) - \operatorname{arctg}\left(\frac{\xi_1}{\zeta_1}\right)\right)\end{bmatrix}, \quad (1)$$

where G is the gravity constant and σ is the density of the body.

For computing in a horizontal prism, the following initial parameters are set: the depth of the upper ζ_1 and lower ζ_2 edges of the anomalous body and the value of the gravity field Δg. For free parameters, we treat the values of the beginning ξ_1 and the end ξ_2 of the profile, and the sought parameter is the optimal density value σ.

3.2. Sphere. The gravity effect from a homogeneous spherical body of radius R and volume V, with excess density $\Delta\sigma$ located at depth h (see Figure 3(b)), in a one-dimensional version is calculated by the formula:

$$g_s = \frac{G\Delta\sigma V h}{R^3} = \mathrm{GM}\frac{h}{(x^2+h^2)^{3/2}} \quad (2)$$

where $M = \Delta\sigma V = \Delta\sigma\frac{4}{3}\pi R^3$ - is the effective mass of a homogeneous spherical body, G is the gravity constant, h is the depth of the body, x is the center of the spherical body, R is the radius, and σ is the density.

We suppose to be known and fixed a pair of body parameters (the center of the sphere x, radius R). For a free parameter, we treat the *average* depth h of the anomalous body. The sought medium parameter to be optimized through the iterative improvement is the density σ of the sphere. If necessary (weak convergence, unsuccessful initial approximation, large residual, etc.), we free the parameters x and R and repeat the iteration cycle again.

3.3. Vertical ledge. We define a vertical ledge as a body of semi-infinite strike, confined by a pair of horizontal planes and a rectangular vertical one (see Figure 3 (c)). Its gravity impact is derived as a special case of the effect for a rectangular parallelepiped. The analytical expression for finding the gravity field Δg_{led} at the point x (along the x axis at $z = 0$, $y = 0$) is as follows:

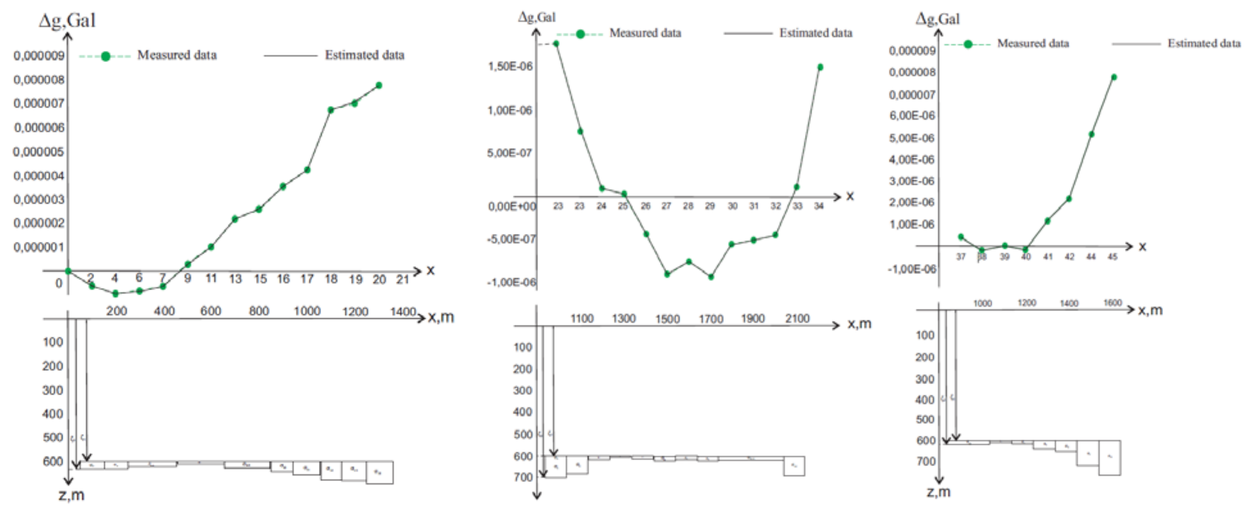
$$g_{\mathrm{led}}(x) = G\Delta\sigma\left[x\ln\frac{x^2+h_2^2}{x^2+h_1^2} + \pi(h_2-h_1) + 2h_2\mathrm{arctg}\frac{x}{h_2} - 2\mathrm{arctg}\frac{x}{h_1}\right] \quad (3)$$

where G is the gravity constant, σ is the density, x is the coordinate of the vertical discharge, h_1 is the depth of the lower horizontal plane and h_2 is the depth of the upper horizontal plane.

For this model, the initial parameters of the algorithm are set as follows: the vertical fault x, the depth of the lower horizontal plane h_1, and the measured gravity value Δg. For a free parameter, we treat the depth of the upper horizontal plane h_2, and the sought one is the density σ of the ledge. However, as we did in other models if necessary, free and fixed parameters can be mutually interchanged.

4. Results and discussions. First of all, we suppose a general condition for all the models mentioned: due to the small number of measurements and the significant distance between the observation points, we assume that the value of gravity at each separate point is the consequence of the integral impact of a separate modeled source of anomalies. That is, gravity at each point is a consequence of the effect of some *material point*, in the center of which is concentrated all of its gravitating mass. Then the conditions of the Poincaré lemma on the sweeping masses to the boundary of a convex region of a harmonic function are valid. Considering this condition, we present the simulated annealing simulation results with known initial parameters of the medium.

4.1. Horizontal prism. The calculations were performed with a step along the profile of 100 m, and the properties of rocks and their depth were taken into account. The charts of gravity anomalies from the model are obtained in the form of a series of horizontal prisms along three profiles (see figure 3). For this model, a solution was found in 6905 iterations at $T = 1000°$ and a cooling rate of 0.001 m/s^2, with a



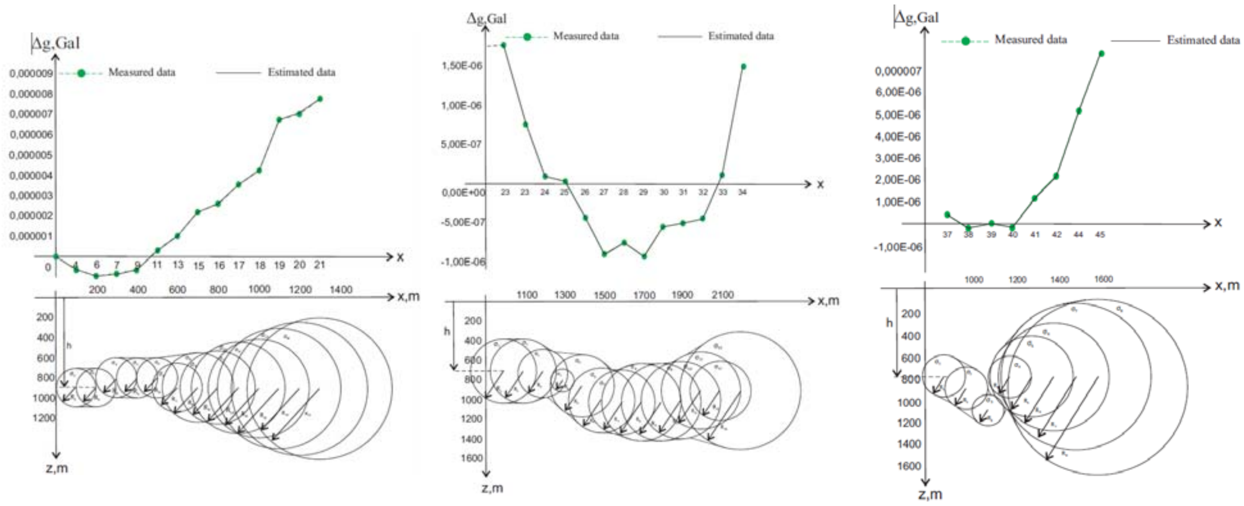
a) along the profile 1-1 b) along the profile 2-2 c) along the profile3-3

Figure 3 – Gravity anomaly from the model given as a series of horizontal prisms

relative error of 15% for ζ_1, ζ_2 and σ. We solve the problem with a constant step in the interval for the density σ and the depth of the spherical body, equal to 0.001. Such a step is defined in order to ensure the numerical stability of the algorithm: the smaller the iteration step, the more accurate the calculation.

In order to simulate the errors in the initial data, we solved the direct problem of gravimetry at a different level of measurement errors (5-20% of the maximum value of the anomaly). A pseudo-random number sensor with a Gaussian distribution (like AnyLogic or ArcGIS) simulates the errors. The average computation time is 3 s, which proves the speed of the algorithm for a small-dimensional data matrix. The relative error of calculations is 2.67% and indicates the accuracy of the approach.

4.2. Sphere. Calculations performed at a depth of 900 m along the profile 3-3 displayed that the solution (the right side of the chart of the gravity field, starting from point 41) has a significant residual of the gravity. We decided to carry out an additional iterative improvement for the entire profile while fitting by other free parameters of the model. This approach has resulted in a model with a good residual of gravity along the entire section (see figure 4). The calculations were performed at T = 1000°, a cooling rate 0.0001 m/s^2, with an error of 15% for ζ_1, x, and σ, with a step equal to 0.001. The relative error of the solution lies within acceptable limits, no more than 0.12%. The average computation time is 6 s. The solution is found at over 69,000 iterations.



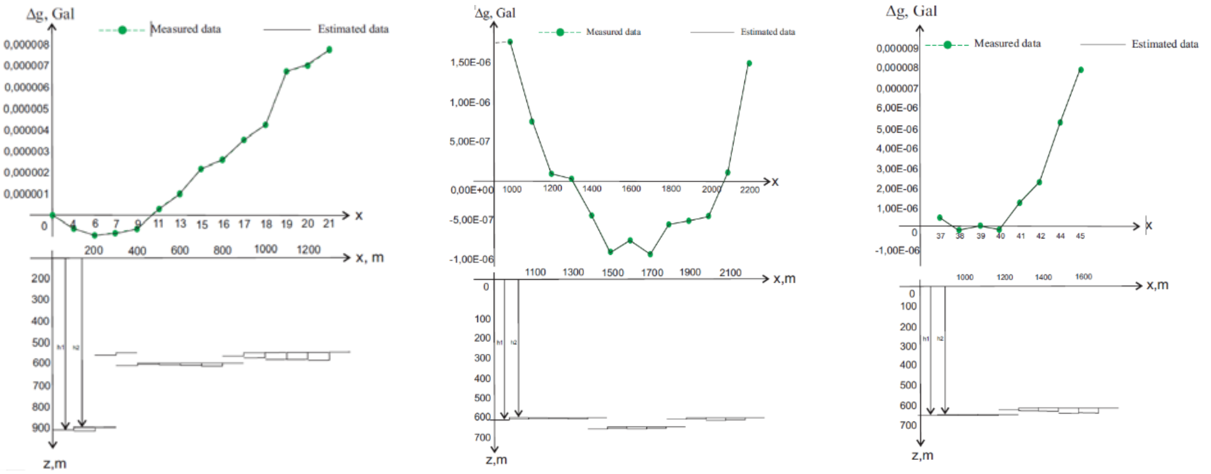
a) along the profile 1-1 b) along the profile 2-2 c) along the profile 3-3

Figure 4 – Gravity anomaly from the model given as a series of spherical bodies

4.3 Vertical ledge. Calculations for a vertical ledge started with a reference depth of 600 m along the profile. At the beginning of profile 1-1, a significant residual arose in the solution, and we subjected this part to additional calculations. The final solution (gravity effects from a set of vertical ledges) for all three profiles were obtained within the acceptable error (see figure 5). The relative measurement error lies within acceptable bounds, no more than 1.26%. The calculations were performed at T = 100° and a cooling rate of 00001. The average duration of computations is 17 s. Each solution was found at over 46,000 iterations.

In general, the results of calculations by simulating annealing approach showed a fairly *stable* solution provided that the initial data bulk is extremely limited. As part of a consistent fitting of parameters, we obtained the final models of the HCR medium under study that have the acceptable likelihood, with the accuracy of the solution by the gravity data is reached 10^{-11}. Thus, the simulated annealing approach allows us to fit quickly the options for suitable solutions for the express analysis of the internal structure of the geological medium within the boundaries of the studied HCR.

Due to the small amount of data, the simulation results have limited applicability and need to be verified using other geophysical methods or by solving the same problems using real field data of significantly larger dimensions.



along the profile 1-1 along the profile 2-2 along the profile 3-3

Figure 5 – Gravity anomaly from the model given as a series of vertical ledges

5. Conclusions. The simulated annealing approach provides a solution to the direct problem of gravimetry for several mathematical models of the geological medium with *sufficient* accuracy. Given the number of iterations and the number of possible combinations of parameters, the technique allows to find quickly the optimal density and depth parameters for homogeneous bodies of regular geometric shape.

While comparing the solutions for different bodies with the same bulk of initial data, it was found that the calculation time depends on the choice of the initial temperature *T* and the cooling rate, i.e. the initial density approximation in the simulated annealing approach. The higher the temperature and the lower the cooling rate, the longer the calculation takes. Thus, for a vertical ledge, the average calculation duration was 17 s at a cooling rate of 0.0001 s. Nevertheless, such a dependence is a common property of all gradient-like solution search methods. Of all the above models, the model of horizontal prisms was calculated faster of all (3 s) at a cooling rate of 0.001 s.

A numerical module for GIS GeoM has been created, which allows you to fit the appropriate parameters of anomalous geological bodies by minimizing the residuals in gravity field trough the simulated annealing approach. Its testing on the example of various bodies and measured values of the gravity field allowed us to increase the reliability of the original HCR model at each profile. Thus, the implementation of this technique improves the accuracy, speed, and stability of solving the gravity direct problems for a multicomponent layered geological medium.

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ЖЕР ҚОЙНАУЫ ЖАҒДАЙЫНЫҢ ГРАВИМЕТРИЯЛЫҚ БАҚЫЛАУ ДЕРЕКТЕРІН ИНТЕРПРЕТАЦИЯЛАУ ҮШІН ИМИТАЦИЯЛЫҚ КҮЙДІРУ ӘДІСІМЕН ГРАВИБАРЛАУДЫҢ ТІКЕЛЕЙ МӘСЕЛЕСІН ШЕШУ

Аннотация. Көмірсутектер шоғырларын ұзақ игеру кезінде геологиялық ортада күрделі деформациялық процестер жүреді. Геодинамикалық қауіп-қатерді және теріс салдарын бағалау үшін гравитациялық мониторинг жүргізіледі. Нәтижесінде үздіксіз өзгеріп отыратын кәсіпшілік-геологиялық жағдайдың өзара байланысы зерттеледі (өндіру көлемінің өзгеруі, қаттық қысымның өзгеруі, флюидті өнімді қаттарға айдау процестері). Өнеркәсіптік қауіптілігі жоғары аймақтарды анықтау кезінде гравитациялық инверсияны шешудің негізгі құралы тікелей гравитациялық есепті шешу болып табылады. Бұл зерттеулерде ортаның берілген бастапқы жақындауына сүйене отырып, тапсырма дәйекті жуықтау арқылы жүзеге асырылады. Мұндай үлестірімдерді бағалау үшін мақала авторлары стохастикалық оңтайландыру аясында модельдеу тазарту әдісін қолдануды ұсынады. Ол гравитациялық өріс мәндерінің минималды қалдығы болған жағдайда оңтайлы орта параметрлерін реттеуге бағытталған.

Тәсіл геологиялық ортаның үш қарапайым математикалық моделін қолдана отырып жүзеге асырылады: көлденең призма, біртекті сфера және тік проекция. Бұл әдіс қоршаған орта мәндерін оның параметрлерінің жұпына сәйкес бір уақытта реттеуге мүмкіндік береді. Алгоритмнің жұмысы сипатталған және модельдеу нәтижелері келтірілген. Алынған нәтижелер ұсынылған әдіспен тікелей гравитациялық есепті шешу алгоритмінің қолайлы дәлдігін көрсетті. Имитациялық тазарту әдісі гравитациялық өрісті талдау уақытын азайту кезінде ГАЖ моделінің сенімділігін арттыруға мүмкіндік берді.

Түйін сөздер: гравиметрияның тікелей мәселесі, имитациялық күйдіру, гравитациялық вариация, гравиметриялық бақылау, көмірсутегі кен орны.

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РЕШЕНИЕ ПРЯМОЙ ЗАДАЧИ ГРАВИРАЗВЕДКИ МЕТОДОМ ИМИТАЦИИ ОТЖИГА ДЛЯ ИНТЕРПРЕТАЦИИ ДАННЫХ ГРАВИМЕТРИЧЕСКОГО МОНИТОРИНГА СОСТОЯНИЯ НЕДР

Аннотация. При длительном освоении залежей углеводородов (УВ) в геологической среде происходят сложные деформационные процессы. Для оценки возможного геодинамического риска и негативных последствий от ГКР проводится гравитационный мониторинг. В результате исследуются взаимосвязи непрерывно меняющейся промыслово-геологической обстановки (изменения объемов добычи, изменения пластового давления, процессы закачки флюида в продуктивные пласты). Основным инструментом решения гравитационной инверсии при определении зон повышенной промышленной опасности является решение прямой гравитационной задачи. В этих исследованиях, исходя из заданного начального приближения среды, задача реализуется путем последовательных приближений. Для оценки таких распределений авторы статьи рекомендуют использовать метод имитационного отжига в рамках стохастической оптимизации. Она направлена на подгонку оптимальных параметров среды при условии, что происходит минимальный остаток значений гравитационного поля.

Подход реализуется с использованием трех простых математических моделей геологической среды: горизонтальной призмы, однородной сферы и вертикального выступа. Этот метод позволяет подгонять значения среды одновременно по паре ее параметров. Описана работа алгоритма и приведены результаты моделирования. Полученные результаты показали приемлемую точность алгоритма решения прямой гравитационной задачи предложенным методом. Метод имитационного отжига позволил повысить надежность модели ГКР при одновременном сокращении времени анализа гравитационного поля.

Ключевые слова: прямая задача гравиметрии, метод имитации отжига, вариации силы тяжести, гравиметрический мониторинг, месторождение углеводородов.

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REFERENCES

[1] Trofimov D.M. (2016) Modern micro-amplitude tectonic movements, remote methods for their study and importance for oil and gas geology // Infra Engineering, M. 80 p. (in Russ.).

[2] Shevelyova A. (2010) Integrated Geodynamic Monitoring and Risk Assessment of Occurrence of Seismic Deformation Processes Related to Development of Raw Hydrocarbon Deposits. SPE Caspian Carbonates Technology Conference, Atyrau, Kazakhstan, 8-10 November; Society of Petroleum Engineers. P. 1-8. https://doi.org/10.2118/139949-MS

[3] Nurpeisova M., Bekbassarov Zh., Kenesbayeva A., Kartbayeva K., Gabitova U. (2020) Complex evaluation of geodynamic safety in the development of hydrocarbon reserves deposits // News of NAS RK. Series of geology and technical sciences. Vol. 1, N 439. P. 90-98. https://doi.org/10.32014/2020.2518-170X.11

[4] Shlyahovskii V.A. (1984). The study of oil and gas prospective structures using a dialogue system for interpreting gravitational anomalies. Dissertation, Institute of Geophysics named after Subbotin S. I. (in Russ.).

[5] Hinze W., Von Frese R., Saad A. (2013) Gravity and Magnetic Exploration: Principles, Practices, and Applications, Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511843129

[6] Zhao L.S., Sen M., Stoffa P., Frohlich C. (2007) Application of Very Fast Simulated Annealing to the Determination of the Crustal Structure Beneath Tibet // Geophysical Journal International. Vol. 125, Issue 2. P. 355-370. https://doi.org/10.1111/j.1365-246X.1996.tb00004.x

[7] Chakravarthi V., Pramod Kumar M., Ramamma B., Rajeswara Sastry S. (2016) Automatic gravity modeling of sedimentary basins by means of polygonal source geometry and exponential density contrast variation: Two space domain based algorithms // Journal of Applied Geophysics. Vol. 124. P. 54-61. https://doi.org/10.1016/j.jappgeo.2015.11.007

[8] Abdelrahman E.M., Sharafeldin S.M. (1995) A least-squares minimization approach to depth determination from numerical horizontal gravity gradients // Geophysics. Vol. 60, Issue 4. P. 939-1278. https://doi.org/10.1190/1.1443857

[9] Nazirova A., Abdoldina F., Dubovenko Y., Umirova G. (2019) Application of the simulated annealing method for gravimetric monitoring data analysis of the bowels condition of oil and gas deposits // Bulletin of the Kazakh National Research Technical University after K.I. Satbayev. Vol. 3, N 133. P. 397-405 (in Russ.).

[10] Nazirova A., Abdoldina F., Aymahanov M., Umirova G., Muhamedyev R. (2016) An Automated System for Gravimetric Monitoring of Oil and Gas Deposits. First International Conference, DTGS 2016, St. Petersburg, Russia, June 22–24 2016, Published in: Communications in Computer and Information Science. Vol. 674. P. 585-595. https://doi.org/10.1007/978-3-319-49700-6_58

[11] Nazirova A., Abdoldina F., Dubovenko Y., Umirova G. (2019) Development of GIS subsystems for gravity monitoring data analysis of the subsoil conditions for oil and gas fields // Geoinformatics 2019, Kyiv, Ukraine, 13-16 May 2019; European Association of Geoscientists & Engineers. P. 1-5. https://www.earthdoc.org/content/papers/10.3997/2214-4609.201902099

[12] Sen M., Stoffa P. (2013) Simulated annealing methods. In Global Optimization Methods in Geophysical Inversion // Cambridge University Press, Cambridge. P. 81-118. https://doi.org/10.1017/CBO9780511997570.006

[13] Singh A., Biswas A. (2016) Application of global particle swarm optimization for inversion of residual gravity anomalies over geological bodies with idealized geometries // Natural Resources Research. Vol. 25. P. 297-314. https://doi.org/10.1007/s11053-015-9285-9

[14] Sheng Z., Xiaohong M., Minghua Z., Zhaoxi C., Chunxiao X., Yajie L. (2018) The improved residual node density based gravity forward method and its application // Journal of Applied Geophysics. Vol. 159. P. 765-772. https://doi.org/10.1016/j.jappgeo.2018.10.020

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