ABSTRACT
of the dissertation for the degree of "Doctor of Philosophy" (PhD) in the specialty 6D070400 - "Computer Science and Software Engineering"

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DEVELOPMENT OF AN INFORMATION SYSTEM FOR PROCESSING GRAVIMETRIC MONITORING DATA USING GLOBAL OPTIMIZATION METHODS (ON THE EXAMPLE OF SOLVING THE GRAVITY DIRECT PROBLEM)

The relevance of research. For the environmentally safe operation of oil and gas fields it is necessary to carry out a multi-method complex of geological exploration. Over the past decades, many computer technologies have been developed for the processing and analysis of geological and geophysical data. A variety of information and analytical technologies based on automated and geographic information systems greatly facilitate the work with large amounts of data, speed up access to the necessary information, and allow operations with heterogeneous objects and models much faster than in the era of early computerization of geophysics. Based on this, an information system (IS) based on open access systems can be considered as an effective tool that implements the basic procedures associated with the storage, processing and analysis of data, as well as providing the necessary display of analysis results.

Despite the presence in the near and far abroad of a number of automated geophysical data processing systems (a review of some of them will be given below), we can state the absence of a full-fledged, easily accessible, narrow-purpose IS for monitoring potential fields in an oil and gas field for the purpose of its controlled operation. Such an IS should be focused primarily on solving the actual problem of processing, storing and express interpretation of gravity survey data and related geological and geophysical information (in particular, data from acoustic monitoring, leveling (i.e. studying the level of deformations), electrical exploration, and etc.). An equally important goal of the IS should be to solve the problems of predicting the parameters of a hydrocarbon deposit during their operation using the complex of the above measurement data in order to optimize the extraction of hydrocarbon reserves and prevent negative geodynamic and environmental consequences due to a change in the operation mode of the deposit. These needs cause an urgent need to develop an effective integrated information system, to the fullest extent possible, solving the above problems.

In our country, complex geodynamic monitoring is carried out by specialized service companies with the necessary equipment and qualified specialists, such companies are the Scientific and Production Center "GEOKEN", the diversified enterprise "Azimut Geology", LLP "GEO ENERGY GROUP", etc.

There are many ready-made specialized software solutions (OASIS MONTAJ, COSCAD 3D, ZondMag3D, VECTOR, SIGMA 3D) that implement a wide range of work with geological and geophysical data for geodynamic and

gravimetric monitoring, but they are expensive, not adapted to the methods and conditions of research, processing, storage and interpretation of data by domestic service companies, the functionality of ready-made software is used by 15-30%, which is not effective.

In this regard, within the framework of the research topic, the task of developing a domestic integrated web-based information system that implements the solution of the problem of gravimetric monitoring of the state of the subsoil according to real-time gravimetry data is relevant. service for processing and interpreting variations of the gravitational field, in conditions of a limited amount of data.

The solution of the direct problem makes it possible not only to reliably determine the nature of gravitational anomalies, but also reduces the possible set (class) of models subjected to analysis, because in the functional sense the problem is a gravitational test. Multiple sequential (iterative) solution of the gravity direct problem with various combinations of parameters of the medium under study underlies one of the leading methods for quantitative interpretation of data from potential geophysical fields - the selection method. In general, the solution of the direct problem means the iterative selection of the optimal parameters of the mathematical model of the geo-environment until the minimum discrepancy between the measured and calculated values of the gravitational field is obtained.

Today, traditional deterministic methods for solving the gravity direct problem hardly meet the increased requirements for accuracy and quality of solutions, especially under conditions of a limited amount of initial data and under conditions of poorly predictable dynamic unloading of the geo-environment, when the speed of decision making is important. The use of multivariate analysis for solving a problem by the selection method increases the resource of time, and the use of heuristic models implies a constant revision of the problem, taking into account the emergence of new information. In addition, the limitations of the RAM of computers determine the use of the minimum number of elementary figures, and the limitations in the computing power of computers in field expeditions slow down the solution of the problem and limit the enumeration of possible solutions. In this regard, it is very important to use probabilistic methods of global optimization of solutions to geophysical problems in a statement in which point sources of anomalies are described by the method of integral representations.

The purpose of the dissertation work is to develop an information system for monitoring and modeling the ecological state of a hydrocarbon deposit. IS will allow modeling the state of the geological and geophysical environment of the field by solving the gravity direct problem using global optimization methods for a number of simple mathematical models of the geological environment of the field within a given productive layer (depth range).

Research objectives. The main objectives of the dissertation research, taking into account all of the above, are defined as follows:

— analysis of existing approaches and techniques for processing and analyzing gravitational anomaly data;

— research, selection and justification of the choice of effective methods for solving the direct gravimetry problem;

— analysis of the principles of IS construction, data modeling rules and technologies for processing and system analysis of information in existing IS to assess environmental parameters and technogenic impact on the environment, design of the developed IS;

— development of the IS module for automation of the methodology of preliminary processing of primary data of field studies of the gravitational field;

— development of an IS module for storing, managing gravimetric research data, as well as post-processing of measurement data and visualization of results;

— development of a numerical IS module for processing gravimetric monitoring data by solving a direct gravimetry problem for a number of specified models of the geological environment (homogeneous sphere, horizontal prism, vertical ledge) by global optimization methods (simulated annealing method and genetic algorithm).

Object of study. The object of the study is the process of assessing and predicting possible negative geodynamic consequences as a result of long-term development of oil and gas fields, based on the development of an integrated information system.

Subject of study. The subject of the research is effective methods for solving the gravity direct problem, as one of the fundamental problems of the theory of interpretation of gravitational fields.

Research methods. In the dissertation work, the following research methods were used in the development of numerical modules: methods for the quantitative solution of the gravity direct problem (in particular, the annealing simulation method, the genetic algorithm); methods of system analysis of models; information processing methods (quick sorting, filtering, normalization, smoothing, etc.); methods of standard statistical data processing (averaging, correlation, factorization, calculation of errors). When creating an IS shell, implicitly (without documentation in the text of the work), CASE technologies for designing and developing information systems were used. In writing the text of the work, methods of advanced search for links, semantic analysis of content are involved.

The scientific novelty of the dissertation research lies in the fact that for the first time the method of simulating annealing and the genetic algorithm, which are probabilistic methods of global optimization, were used to solve the gravity direct problem, the effectiveness of the methods used and the developed algorithms for solving the gravity direct problem was evaluated.

The main scientific provisions submitted for defense:

1. An effective method for solving a direct gravimetry problem using probabilistic methods of global optimization: simulated annealing method, genetic algorithm. By solving a series of direct problems, the inverse gravimetry problem is solved. The proposed method makes it possible to determine with satisfactory accuracy and high speed the parameters of anomaly-forming bodies of simple geometric shape by a known value of the gravitational field.

2. An algorithm for automated pre- and post-processing of primary data from field studies of changes in the gravitational field at a hydrocarbon deposit.

3. Architecture of a new integrated web-oriented information system that combines all stages of processing and analysis of gravimetric research data for modeling the density structure of the subsurface of the studied territory of the hydrocarbon deposit.

Despite the presence of separate automated and information systems for processing geophysics data and solutions to gravimetry problems by separate methods of global optimization for individual models of the environment, it is the choice of several models of the environment, their analysis by several optimization methods, and the integration of models and calculation methods in the IC – as a whole – has no analogues among the known geophysical ICS.

Connection of the topic with the plans of research programs. The presented results were obtained during the implementation of the Satbayev University project on the topic "Development of a geoinformation system for solving the problem of gravimetric monitoring of the state of the subsoil of oil and gas regions of Kazakhstan based on high-performance computing in conditions of a limited amount of experimental data" No. AP05135158 (grant funding for scientific projects of the Ministry of Education and Science of the Republic of Kazakhstan for 2018-2020).

Practical and theoretical significance of the obtained results. The practical value of the study lies in the creation and testing of an information system that meets existing standards, and with its help in solving a number of test problems with a limited set of real initial data. The use of the developed information system based on global optimization methods makes it possible to reduce the time spent on searching for the parameters of simple models of the geological environment according to the gravity field data.

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The theoretical significance of the results of the applicant's work is as follows:

— explored and demonstrated the possibilities of using the genetic algorithm and the annealing simulation method in solving the gravity direct problem;

— a sufficiently accurate search for the parameters of anomaly-forming bodies of a simple geological form was carried out, which makes it possible to refine the geological and geophysical models of the environment by the gravitational field.

Approbation of the research results. The main provisions and results of the study were reported at many international scientific conferences:

1) Digital transformation and global society. First international conference DTGS 2016, St. Petersburg, Russia (2016, Scopus);

2) 18th International conference on geoinformatics: Theoretical and applied aspects, Ukraine (2019, Scopus);

3) 20th International conference on geoinformatics: Theoretical and applied aspects, Ukraine (2021, Scopus);

4) 22nd Oil and Gas Exploration and Development Conference "Geomodel 2020", Russia (2020, Scopus);

5) 20th International multidisciplinary scientific geo-conference, SGEM, Bulgaria (2020, Scopus);

6) XVI International scientific conference “Monitoring of geological processes and ecological condition of the environment”, Ukraine (2022, Scopus).

The main results of the study were published in the Eastern-European Journal of Enterprise Technologies (impact factor 2.0, Q3 quartile) and News of the national academy of sciences of the republic of Kazakhstan, Series of geology and technical sciences (impact factor 2.0, Q3 quartile).

Publications. On the topic of the dissertation, 13 papers were published, of which 2 articles were published in journals included in the Scopus and Web of Science databases (both articles are included in Q3), 3 articles were published in publications recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, 5 articles in journals with CiteScore in Scopus without an assigned quartile, 3 articles were published in collections of international scientific and practical conferences. Issued 2 copyright certificates for the results of the work No. 13336 dated November 19, 2020 and No. 28492 dated August 25, 2022.

The structure and scope of the dissertation. The dissertation consists of an introduction, four sections, a conclusion, a list of references and applications.

The introduction substantiates the relevance of the topic of the dissertation work, formulates the purpose of the research, identifies the main tasks to achieve the goal, reflects the scientific novelty and practical value of the work, and gives a general description of the work.

The content of the dissertation is built according to the classical principle: review of problems - improvement methodology - system development - testing and analysis of results. Therefore, *the first chapter* of the work is devoted to a review of the causes and methods for predicting geodynamic phenomena in hydrocarbon fields, including some vivid examples of negative consequences, as well as an analysis of the possibilities of gravity monitoring. The review ends with a brief analysis of existing information technologies for assessing the anthropogenic impact at hydrocarbon production sites using geophysical means. The conclusions to the chapter summarize the narrow focus of these technologies and confirm the relevance of research.

The second chapter highlights the methodology for assessing geodynamic processes using the example of procedures for measuring and processing gravimetric data immediately in the environment of the information system (IS) being developed, including selection, rejection, smoothing, reduction, calculation of field anomalies, assessment of measurement accuracy, visualization and database formation. Processing and comparison of monitoring data are organized by

measurement cycles, and within a cycle - by sets of survey methods, including well logging data, with subsequent storage in a database on a server in *.xls format.

A generalized method for estimating the parameters of medium models by solving the gravity direct problem (PGG) in a deterministic formulation for a number of geometrically regular bodies is described. A review of the possibilities of genetic methods for stochastic global optimization of the solution of the CGG is given. The choice of specific algorithms (simulation of annealing, genetic algorithm) is substantiated, including, as a possibility of simultaneous optimization of several parameters of the geo-environment, adaptation of parameters to new conditions, reduction of steps of a priori conditioning of the initial model of the environment. The implementation of the steps of the above algorithms for three different mathematical models of the environment is described. Consistent selection of environment parameters according to several of its initial models is a significant advantage of the structure of the developed IS.

The third chapter reflects the functional model of the workflows of the IS and its various components, as well as the results of its decomposition into various levels and functions (preprocessing, anomaly calculation, CGD solution, visualization, summary database, optimization), including the functions of cartographic visualization, more typical for GIS. The general IS diagram is presented in the subsection devoted to the aspects of creating a database, as the main component of IS, based on PostgreSQL. The software implementation of the procedure for processing measurements by cycles of observations, including error handling, introduction of corrections, and creation of summary profiles of vertical displacements based on leveling data, is covered in detail. The latter possibility significantly enriches the IS and makes it complex. The interface of numerical modules for solving the DGG (data input, calculation) and aspects of data visualization (stylization, vector overlay) are demonstrated. One can argue about the design of screen forms, but their performance has been proven by experience. The result of the design is the logical integration of modules into a single IS shell.

The final, *fourth chapter* is devoted to testing workflows and numerical stability of IS by solving a series of test problems. As a result of solving and analyzing a number of test (synthetic) examples, good stability and acceptable efficiency of the IS in terms of accuracy and speed were shown.

In *conclusion*, the results of the work done in the framework of the dissertation work are summed up.

The content of the dissertation ends with *a list of references* and *applications*.