ТЕХНИЧЕСКИЕ НАУКИ
И ТЕХНОЛОГИИ

ЕСЕПТЕУ МАТЕМАТИКАСЫ, САНДЫҚ ТАЛДАУ,
МАТЕМАТИКАЛЫҚ ЖӘНЕ КОМПЬЮТЕРЛІК МОДЕЛЬДЕУ
ВЫЧИСЛИТЕЛЬНАЯ МАТЕМАТИКА, ЧИСЛЕННЫЙ АНАЛИЗ,
МАТЕМАТИЧЕСКОЕ И КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ
COMPUTATIONAL MATHEMATICS, NUMERICAL ANALYSIS,
MATHEMATICAL AND COMPUTER MODELING

DOI 10.51885/1561-4212_2023_4_267
IRSTI 50.41.29

A.T. Kussainova[1], Z.O. Oralbekova[1], M.G. Zhartybayeva[1], N. Serik[2]
[1]L.N. Gumilyov Eurasian national university, Astana city, Kazakhstan
E-mail: ainurkussainova89@gmail.com
E-mail: oralbekova@bk.ru
*E-mail: makkenskii@mail.ru**
[2]Company KazZINK
E-mail: nurzhan.serik1990@gmail.com

THE INTERPRETATION TECHNIQUE OF GEOPHYSICAL DATA BY USING IT

IT ҚОЛДАНУМЕН ГЕОФИЗИКАЛЫҚ ДЕРЕКТЕРДІ ТҮСІНДІРУ ӘДІСНАМАСЫ

МЕТОДИКА ИНТЕРПРЕТАЦИИ ГЕОФИЗИЧЕСКИХ ДАННЫХ С ПРИМЕНЕНИЕМ IT

Аңдатпа. *Қазіргі уақытта өнімділігі жоғары есептеуіш технологияларды пайдалана отырып, геофизиканың қолданбалы есептерін шешу үшін алгоритмдер мен бағдарламалық қамтамасыз етуді әзірлеудің өзекті қажеттілігі туындап отыр. Осыны ескере отырып, бұл жұмыстың мақсаты геологиялық қималар деректерінің репозиторийін және таңдау әдісіне ыңғайлы веб-қосымшаны құру болып табылады. Бұл қолданба академик А.Н. Тихонов ұсынған үйлестіре таңдау әдісін қолдана отырып, мақсатты кластар мен пайдаланылатын орта үлгілеріне негізделген деректерге оңай қол жеткізуді қамтамасыз етеді. Авторлар әртүрлі техникалық сипаттамалары бар заманауи радиолокациялық жүйелерді пайдалана отырып, бірқатар эксперименттерді сәтті жүргізді. Бұдан басқа, олар аймақта бұрыннан бар үлгілерден шағылысқан сигналдарды тіркеп, қосымша өлшеулер жүргізілді. Теориялық болжамдарды эксперименттік бақылауларға қарсы қоя отырып, жан-жақты салыстырмалы талдау жүргізілді. Бұл талдау геологиялық кескіндердің деректер қорында сақталған қазіргі заманғы радиолокациялық деректердің үлкен көлеміне негізделген.*

Түйін сөздер: *Георадар, ақпараттық технологиялар, геофизикалық деректерді түсіндіру, программалық қамтамасыздандыру.*

Аннотация. *В настоящее время существует насущная потребность в разработке алгоритмов и программного обеспечения для решения прикладных задач геофизики с использованием высокопроизводительных вычислительных технологий. Принимая это во внимание, целью данной работы является создание хранилище данных геологических разрезов и удобное web-приложение для метода подбора. Это приложение основывается на методе подбора, предложенный академиком А.Н. Тихоновым и обеспечивает удобный доступ к данным, организованным на основе целевых классов и конкретных используемых моделей среды. Авторы успешно провели серию экспериментов с использованием современных радиолокационных систем с различными техническими характеристиками. Кроме того, они провели дополнительные измерения, зафиксировав отраженные сигналы от ранее существовавших образцов на полигоне. Был проведен всесторонний сравнительный анализ, противопоставляющий теоретические предсказания экспериментальным наблюдениям. Этот анализ основан на большом количестве современных радиолокационных данных, хранящихся в базе данных геологических разрезов.*

Ключевые слова: *Георадар, информационные технологии, интерпретация геофизических данных, программное обеспечение.*

Abstract. *Currently, there is a pertinent need for the development of algorithms and software to address applied challenges in geophysics, utilizing high-performance computing technologies. Taking this into account, the goal of this work is to create a repository of geological sections data and a convenient web application for the selection method. This application is based on the selection method proposed by academician A.N. Tikhonov and provides convenient access to data organized on the basis of target classes and specific medium models employed. The authors have successfully executed a series of experiments employing contemporary radar systems with diverse technical specifications. Moreover, they conducted supplementary measurements by capturing reflected signals from pre-existing samples within the test site. A comprehensive comparative analysis has been conducted, contrasting theoretical predictions with experimental observations. This analysis relies on the wealth of modern radar data stored within the geological cross-section data repository.*

Keywords: *Ground Penetrating Radar, information technologies, interpretation of geophysical data, software.*

Introduction. Georadar systems, often referred to as GPR, find application in non-destructive assessment and diagnostics across various domains like construction, road surfaces, and archaeological investigations. These systems emit electromagnetic signals into the surveyed environment, capturing and recording the ensuing reflected electromagnetic signals. Subsequently, these captured signals are employed to generate a radarogram, which visually represents the time taken by the signal to travel from the observation point to anomalies within the medium. This time information is crucial for solving the inverse problem associated with the study.

The primary objective of these empirical investigations revolves around the interpretation of the radarograms. The methodology employed for these studies relies on engineering principles, encompassing the comparison of acquired radarograms against established standards. Additionally, supplementary calculations are conducted based on the theoretical principles governing wave propagation within the medium.

The authors' works [1-3] detail both practical and theoretical approaches to subsurface radar techniques. The accuracy of radarogram interpretation is largely contingent on the expertise of specialists like geophysicists, whose involvement introduces notable inaccuracies.

Conversely, an alternative avenue in radarogram interpretation involves mathematical and computer modeling of electromagnetic wave propagation and reflection within a medium. While radarograms provide insights into travel times to anomalies, practical interest centers around deducing the physical properties of these anomalies. For reflected electromagnetic signals, the pertinent physical attributes encompass dielectric and magnetic permeability, as well as media conductivity. The pursuit of these coefficients has led to the proliferation of the theory of ill-posed and inverse problems [1], [4-6]. The theoretical underpinnings for inverse problems within mathematical physics were expounded in V.G. Romanov's work [6].

In-depth exploration of inverse problems in geoelectrics and numerical solution methods for these issues is available in the publications of K.T. Iskakov [7-9]. Articles [8, 9] elaborate on the visualization of acquired data for subsequent interpretation. They encompass the visualization of georadar data and elucidate GPR signal processing programs designed to interpret subsurface geological contexts.

A comprehensive analysis of the technical specifications of commonly used georadars, along with considerations in their application for data interpretation, is documented in a collective monograph [10]. Typically, resolving inverse coefficient problems necessitates supplementary information – specifically, the medium’s response at the observation point. In practice, GPR data, specifically the reflected signals from media inhomogeneities captured by the device’s receiver, are utilized. Consequently, GPR captures the time taken by reflected signals, which, in conjunction with built-in software designed to solve inverse problems, facilitates the determination of the geoelectric section.

Materials and methods of research. The entirety of the investigations took place within the confines of a specialized research test site situated at L.N. Gumilyov Eurasian National University. Commencing in 2014, the site has seen the creation of over 20 objects earmarked for research purposes. Initial findings from these endeavors were previously made public by the authors [11, 12]. All resulting empirical data have been meticulously stored within a dedicated data repository. Moreover, to facilitate a more comprehensive and precise examination, additional structures were constructed within clean sand. These new installations encompass updated parameters such as dielectric and magnetic inductivity, as well as medium conductivity. In tandem with these enhancements, modern radar systems equipped with improved antennas were chosen for the experiments [13, 14].

The created web application is based on the selection method [1]. The technique of “selection” represents a prevalent approach in computational practice to achieve an approximate solution for an equation of the following form: $\mathrm{Az} = u$, vu $\in U, z \in F$, where $U, F$are measurement domains.

In employing this technique, a comprehensive range of potential media is considered, and the corresponding calculated physical fields are determined. The aim is to identify any conceivable medium structure in which the calculated physical field closely aligns with the observed field. This identified medium structure is then considered a viable solution to the problem. The selection method is as follows. For a particular element z within a predefined subset of potential solutions $M (M \subset F)$, the operator A is computed, in other words, a direct problem is being solved. We consider the element z_0 from the set M as an approximate solution, in which the disparity $\rho_u(\mathrm{Az}_0, u) = \inf_{z \in M} \rho_u(\mathrm{Az}, u)$ reaches the lowest point [1].

In our scenario, the "selection" method operates as follows: let's assume $M^{(1)}\left(\varepsilon_n, \sigma_n, h_n^{(s)}\right), M^{(2)}\left(\varepsilon_n^{(s)}, \sigma_n, h_n\right), M^{(3)}\left(\varepsilon_n, \sigma_n^{(s)}, h_n\right)$ is classes of potential medium configurations (geoelectric sections), where $h^{(s)} = h^{(s-1)} + \delta h^{(s)}$, $\sigma^{(s)} = \sigma^{(s-1)} + \delta\sigma^{(s)}$, s =0,1,2… is variation parameter, h is thickness of model layers. As mentioned earlier, we address a sequence of direct problems $\mathrm{Az}_j = u_j, j = \overline{1, n}$. From this point, it is not challenging to deduce the category of media responses at a specific observation point, that is $z_j(x, t) = g^j(t)$. Suppose the readings from the instrument (GPR) are established at the observation point, namely $f^j(t)$. Following the "selection" approach, we compute the disparity $\rho_u^j\left(\mathrm{Az}_j\ , u\right) = \inf_{z_j \in M} \rho_u\left(\mathrm{Az}; u_j\right)$. An element that results in the lowest disparity represents the medium's response, and based on this response, the medium is identified within the $M\ ^j$ designated class. Consequently, the challenge of interpreting georadar data will be resolved.

The technique of “selection” represents a prevalent approach in computational practice to achieve an approximate solution for an equation of the following form: $\mathrm{Az} = u$, vu $\in U, z \in F$, where $U, F$are measurement domains.

Results and discussion. Throughout the research, a comprehensive dataset of algorithmic solutions was compiled to form a category encompassing potential calculated physical fields. This collection facilitated the selection of geological section models in scenarios involving layered media.

The algorithms for numerical construction were developed in line with the overarching theory of difference schemes [15]. To illustrate the functioning of the algorithm, Figure 1 offers a visual representation of the numerical solution to forward problems for conceivable layered medium structures.

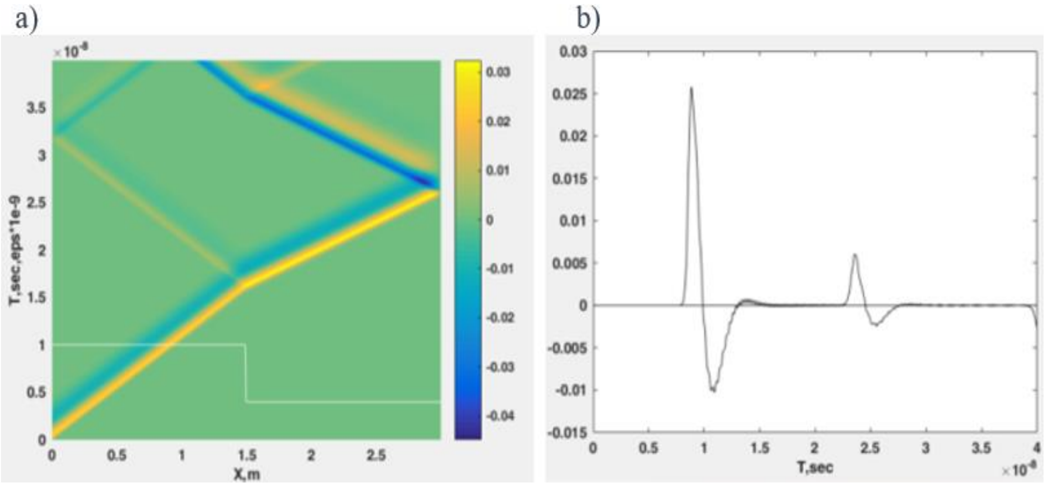

Figure 1. Numerical resolution of direct challenges concerning the potential configuration of a layered medium: a) Signal propagation b) Medium's reaction within a stratified substrate

By altering the fundamental attributes of the media such as permittivity, medium conductivity, and layer thickness, a notably extensive array of potential media configurations was established. A sequence of forward problems was tackled for every classification of feasible media structures. Employing the “selection” approach alongside the established set of benchmarks, inverse problems related to the geoelectrical equation were addressed. The findings and trials associated with the development of fresh mathematical software for processing georadar data are outlined in the publication [16].

As part of the development process, a repository was established, containing geological section data that is categorized by target classes and the specific medium model utilized. Furthermore, a web application was crafted, leveraging contemporary high-performance technologies to offer users convenient access to the data. The software's primary focus centers on addressing a key challenge in geophysics is determining the geoelectric section and interpreting radarograms. This is achieved by employing the engineering method previously detailed, which involves comparing obtained radarograms against established standards and performing supplementary calculations based on wave propagation theory within the medium.

The database itself is constructed using MS SQL Server, while the software application is engineered using the object-oriented programming language Java. The architecture of the data repository and user instructions for the system are elucidated in the article [17]. For an exhaustive exploration of the system, one can visit http://5.63.119.47:8080.

To cater to diverse user needs, the web application offers functionality across three main sections: “Radars” (comprising a list of available radars, their descriptions, and antenna specifications), “Objects of Study” (encompassing characteristics, dimensions, and electrophysical properties), and “Medium Model” (enlisting layer characteristics, electrophysical properties, and electromagnetic wave propagation velocities within the medium).

All experiments conducted at the research site have been documented within the data repository. Figure 2 illustrates the interface of the “Experiments” window, designed to visualize the outcomes of the conducted experiments. To formulate a new experiment, users need to input details such as its name, date, the radar employed, profile depth, experiment duration, and the subjects of the experiment. Additionally, the “Experiments” menu provides not only experiment-related information but also facilitates functions such as editing records and generating new entries.

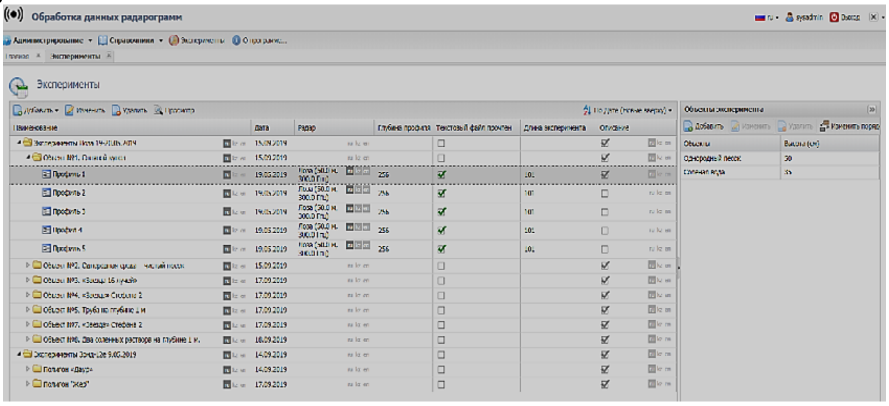

Figure 2. Menu labeled as "Experiments"

Consequently, the user of the developed system gains access to an "Experiment Card" and photographic resources. To provide a visual representation of the system's functionality, a visual examination (depicted in Figure 3) was presented, displaying comparisons between the acquired radarograms and the existing standards within the database.

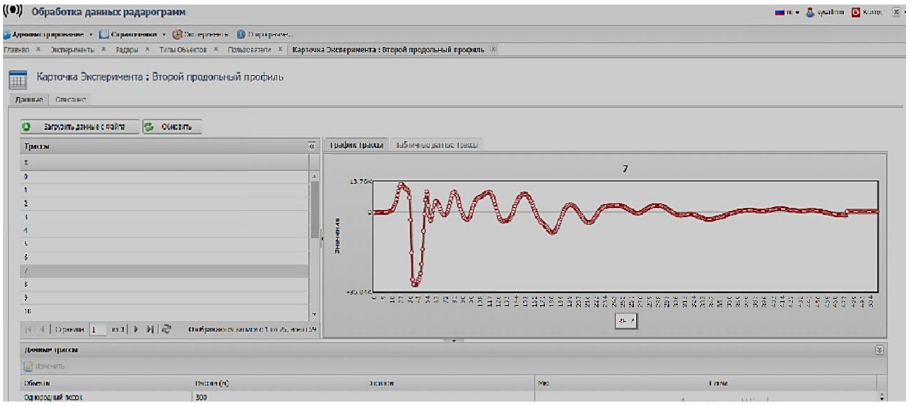

Figure 3. Visualization of viewed experiments

The software that was developed features a user-friendly interface and serves as a valuable tool for conducting geophysical investigations.

Moreover, users have carried out an analysis of geophysical data, akin to the procedures outlined in the studies conducted by the authors [16-17].

Conclusions. Throughout the study, experimental measurements were executed to capture reflected signals from pre-established objects. Subsequently, a data repository was established and populated with geological section data. This repository is organized into target classes and follows the medium model used.

Concurrently, a software application was developed as part of the study. This software facilitates the comparison of experimental radarograms with predefined standard types available within the database. Additionally, it enables supplementary calculations based on the theory of wave propagation within a medium.

The work was carried out with the support of a grant from the Ministry of Education and Science of the Republic of Kazakhstan within the framework of the project IRN AP09058557 under agreement No63-KMU2 dated February 24, 2021

Список литературы

1. Alqahtani, A., Mach, T. & Reichel, L. Solution of ill-posed problems with Chebfun. Numer Algor 92, 2341–2364 (2023). https://doi.org/10.1007/s11075-022-01390-z
2. Гусев, А.П., Моляренко, В.Л., Павловский, А.И., Прилуцкий, И.О., & Андрушко, С.В. (2021). Малоглубинная геофизика при оценке состояния геологической среды промышленных зон (на примере полигона твердых отходов Гомельского химического завода). Вестник ВГУ. Серия: Геология, (4), 63-70. https://doi.org/10.17308/geology.2021.4/3791
3. Копейкин В.В. Рефракция волн в линейных средах с частотной дисперсией. – Москва: Наука, 2017. – 142 с. – ISBN 978-5-02-036038-9.
4. А.Г. Черных, Частотная зависимость локализации индукционных токов, Междунар. науч.-исслед. журн., 2017, выпуск 5, 158–161 DOI: 10.23670/IRJ.2017.59.001
5. Chernykh A. G. Raschet processa samoorganizacii vihrevyh indukcionnyh tokov v massivnom provodnike cilindricheskoj formy pri izmenenii chastity vneshnego kvazistacionarnogo magnitnogo polya svidetelstvo o gos. registracii programmy dlya EhVM 2017611384 Ros. Federaciya [Calculation of the process of self organization of vortex induction currents in a massive conductor of cylindrical shape with a change in the frequency of an external quasistationary magnetic field: Registration of the computer program № 2017611384 Ros. Federation] / A. G. Chernykh; publ. 02.02.2017. bul. № 2
6. Oralbekova Z., Khassenova Z., Mynbayeva B., Zhartybayeva M., Iskakov K. Information system for monitoring of urban air pollution by heavy metals (2021) Indonesian Journal of Electrical Engineering and Computer Science, 22 (3), pp. 1590 - 1600, DOI: 10.11591/ijeecs.v22.i3.pp1590-1600, https://www.scopus.com/inward/record.uri?
7. Snitsar L.R., Iskakov K.T., Zhartybaeva M.G., Suleimenov B.K., Boranbaev S.A. Methodology for the Study of Defects in Technical Structures at Construction Sites, (2022) International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices, EDM, 2022-June, pp. 679 - 682, DOI: 10.1109/EDM55285.2022.9854875
8. Iskakov K., Tokseit D., Boranbaev S., Akhmetov I., Gelbukh I. Computer Modeling of the Outgoing GPR Signal // Computacion y Sistemas. – 2023. – Vol.27(1). – P. 5-12.
9. Mukanova B.G., Iskakov K.T., Kembay A.S., Boranbaev S.A. Inverse source identification problem for the wave equation: An application for interpreting GPR data // Eurasian Journal of Mathematical and Computer Applications. – 2020. – Vol.8 (3). – P. 78-91.
10. Искаков К.Т., Муканова Б.Г., Боранбаев С.А. и др. Алгоритмы и технические средства георадиолокации. – Астана: ЕНУ, 2016. – 124 с.
11. Oralbekova Z.O., Tyulepberdinova G.A., Gaziz G.G., Adamova A.D., Sholpanbaev B.B. The use of radar technologies in the hydraulic engineering in seismic zones // Journal of Applied Engineering Science. – 2021. – Vol. 19(4). – P. 1040-1048.
12. Kabanikhin S.I., Iskakov K.T., Sholpanbayev B.B., Shishelenin M.A., Tokseit D.K. Development of a mathematical model for signal processing using laboratory research data // Bulletin of the Karaganda University. – Vol. 4(92). – 2018. – P. 148-157.
13. Oralbekova Z., Tyulepberdinova G., Gaziz G., Adamova A., Sholpanbaev B. Results of experimental georadar surveys of railway sections // International Journal of GEOMATE. – 2023. – Vol. 25(109). – P.189-196.
14. Iskakov K.T., Mukanova B.G., Berdyshev A.S., Kembay A.S., Tokseit D.K. Mathematical modeling of the source and environment response for the equation of geoelectrics // Bulletin of the Karaganda University. Mathematics Series. – 2019. – Vol. 94 (2). – P. 129-140.
15. Karchevsky, A.L. Analytical Solutions to the Differential Equation of Transverse Vibrations of a Piecewise Homogeneous Beam in the Frequency Domain for the Boundary Conditions of Various Types, (2020) Journal of Applied and Industrial Mathematics, 14 (4), pp. 648-665. http://www.springer.com/mathematics/journal/11754 , doi: 10.1134/S1990478920040043
16. Iskakov K.T., Tokseit D.K., Oralbekova Zh.O., Mirgalikyzy T. Creation and testing of a new mathematical software for processing georadar data // Eurasian Journal of Mathematical and Computer Applications. – 2019. - Vol. 7(4). – P. 86-99.
17. Искаков К.Т., Муканова Ж.А., Баранчук К.И., Оралбекова Ж.О., Омарханова Д.Ж. Характеристики и интерфейс базы данных сигнала по данным георадара // Вестник Евразийского национального университета имени Л.Н. Гумилева». – 2019 г. – № 4(129). – С. 91-100.

References

1. Alqahtani, A., Mach, T. & Reichel, L. Solution of ill-posed problems with Chebfun. Numer Algor 92, 2341–2364 (2023). https://doi.org/10.1007/s11075-022-01390-z
2. Gusev, A. P., Molyarenko, V. L., Pavlovsky, A. I., Prilutsky, I. O., & Andrushko, S. V. (2021). Shallow geophysics in assessing the state of the geological environment of industrial zones (on the example of the solid waste landfill of the Gomel Chemical Plant). Bulletin of VSU. Series: Geology, (4), 63-70. https://doi.org/10.17308/geology.2021.4/3791
3. Kopeikin V.V. Wave refraction in linear media with frequency dispersion. - Moscow: Nauka, 2017. - 142 p. – ISBN 978-5-02-036038-9.
4. A. G. Chernykh, Frequency dependence of the localization of induction currents, Intern. scientific research journal, 2017, issue 5, 158–161 DOI: 10.23670/IRJ.2017.59.001
5. Chernykh A. G. Raschet processa samoorganizacii vihrevyh indukcionnyh tokov v massivnom provodnike cilindricheskoj formy pri izmenenii chastity vneshnego kvazistacionarnogo magnitnogo polya svidetelstvo o gos. registracii programmy dlya EhVM 2017611384 Ros. Federaciya [Calculation of the process of self organization of vortex induction currents in a massive conductor of cylindrical shape with a change in the frequency of an external quasistationary magnetic field: Registration of the computer program No. 2017611384 Ros. Federation] / A. G. Chernykh; publ. 02.02.2017. bul. No. 2
6. Oralbekova Z., Khassenova Z., Mynbayeva B., Zhartybayeva M., Iskakov K. Information system for monitoring of urban air pollution by heavy metals (2021) Indonesian Journal of Electrical Engineering and Computer Science, 22 (3), pp . 1590 - 1600, DOI: 10.11591/ijeecs.v22.i3.pp1590-1600, https://www.scopus.com/inward/record.uri?
7. Snitsar L.R., Iskakov K.T., Zhartybaeva M.G., Suleimenov B.K., Boranbaev S.A. Methodology for the Study of Defects in Technical Structures at Construction Sites, (2022) International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices, EDM, 2022-June, pp. 679 - 682, DOI: 10.1109/EDM55285.2022.9854875
8. Iskakov K., Tokseit D., Boranbaev S., Akhmetov I., Gelbukh I. Computer Modeling of the Outgoing GPR Signal // Computacion y Sistemas. - 2023. - Vol.27(1). – P. 5-12.
9. Mukanova B.G., Iskakov K.T., Kembay A.S., Boranbaev S.A. Inverse source identification problem for the wave equation: An application for interpreting GPR data // Eurasian Journal of Mathematical and Computer Applications. - 2020. - Vol.8 (3). – P.78-91.
10. Iskakov K.T., Mukanova B.G., Boranbaev S.A. and other Algorithms and technical means of georadar. - Astana: ENU, 2016. - 124 p.
11. Oralbekova Z.O., Tyulepberdinova G.A., Gaziz G.G., Adamova A.D., Sholpanbaev B.B. The use of radar technologies in the hydraulic engineering in seismic zones // Journal of Applied Engineering Science. - 2021. - Vol. 19(4). - P. 1040-1048.
12. Kabanikhin S.I., Iskakov K.T., Sholpanbayev B.B., Shishelenin M.A., Tokseit D.K. Development of a mathematical model for signal processing using laboratory research data // Bulletin of the Karaganda University. – Vol. 4(92). - 2018. - P.148-157.
13. Oralbekova Z., Tyulepberdinova G., Gaziz G., Adamova A., Sholpanbaev B. Results of experimental georadar surveys of railway sections // International Journal of GEOMATE. - 2023. - Vol. 25(109). – P.189-196.
14. Iskakov K.T., Mukanova B.G., Berdyshev A.S., Kembay A.S., Tokseit D.K. Mathematical modeling of the source and environment response for the equation of geoelectrics // Bulletin of the Karaganda University. Mathematics Series. - 2019. - Vol. 94(2). - P. 129-140.
15. Karchevsky, A.L. Analytical Solutions to the Differential Equation of Transverse Vibrations of a Piecewise Homogeneous Beam in the Frequency Domain for the Boundary Conditions of Various Types, (2020) Journal of Applied and Industrial Mathematics, 14(4), pp. 648-665. http://www.springer.com/mathematics/journal/11754, doi: 10.1134/S1990478920040043
16. Iskakov K.T., Tokseit D.K., Oralbekova Zh.O., Mirgalikyzy T. Creation and testing of a new mathematical software for processing georadar data // Eurasian Journal of Mathematical and Computer Applications. - 2019. - Vol. 7(4). – P. 86-99.
17. Iskakov K.T., Mukanova Zh.A., Baranchuk K.I., Oralbekova Zh.O., Omarkhanova D.Zh. Characteristics and interface of the signal database according to georadar data // Bulletin of the Eurasian National University named after L.N. Gumilyov". - 2019 - No. 4 (129). - P.91-100.